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Mangroves: Biodiversity, Livelihoods and Conservation

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Part I
General Aspects

Chapter 1
Mangroves: A Unique Ecosystem and Its Significance

Sudhir Chandra Das, Pullaiah Thammineni, and Elizabeth C. Ashton

Abstract Mangroves constitute a unique forest ecosystem at the land–sea interface of the estuarine region in tropical and subtropical countries. The tidal environment and waterlogged soil with often dense anaerobic mud mean that the trees have adapted to survive with a range of aerial roots. The structural complexities of the mangrove vegetation create a unique environment which provides ecological niches for a wide variety of organisms both marine and terrestrial. The productive and biologically rich ecosystem provides many goods and services which are highly valuable and contribute significantly to the livelihoods, well-being and security of coastal communities both locally and globally. Mangrove exploitation, loss and degradation make mangroves a threatened ecosystem but increasing recognition of the importance of mangrove ecosystems for both biodiversity and human well-being is driving efforts around the world to conserve, better manage and restore these ecosystems.

Keywords Adaptations · Goods · Services · Value · Importance

1.1 Introduction

Why mangroves? A question often been asked. However, the once thought of muddy smelly dangerous mosquito-ridden place is now being appreciated for its beautiful diverse habitat and unique species, its many important ecosystem services supporting local communities and also having a global level of importance in combatting climate change. We have all worked in these ecosystems and have diverse experiences that we wanted to bring together in one book with other experts

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from around the world to learn and appreciate the mangroves of the world, their biodiversity, livelihoods and conservation strategies.

In this chapter, we introduce mangroves, their ecosystem and local and global significance briefly. Further chapters will go into more detail about the mangrove plant species and their silviculture (Chap. 2), reproductive ecology (Chap. 3), ethnobotany (Chap. 5), ecosystem services (Chap. 6) and how they support livelihoods (Chap. 7). Advances in remote sensing (Chap. 4) give an idea of losses and gains in mangrove area over time and the effects of climate change (Chap. 8) predict possible future scenarios. Threats to mangroves and conservation strategies (Chap. 10) and rehabilitation and restoration of mangroves (Chap. 9) are some of the general topics covered in this book. Part II gives the country case studies from around the world. We start from India (Chaps. 11 and 12 for Sundarbans) and travel around Asia to Sri Lanka (Chap. 13), Myanmar (Chap. 14), Malaysia (Chap. 15), Indonesia (Chap. 16), Philippines (Chap. 17), Japan (Chap. 18) to South America Ecuador (Chap. 19), Brazil (Chap. 20) and Africa Cameroon (Chap. 21).

1.2 Mangrove Definition

Several mangrove experts have recognised and defined the term "Mangrove" differently:

Davis Jr (1940) defined mangroves as "Plants which live in muddy, loose, wet-soils in tropical tidewater." MacNae (1968) defined mangroves as "Trees or bushes growing between the levels of high water of spring tide and level close to, but above the mean sea level." He also used the term "Mangal" for referring to the mangrove forest community, while the term "Mangrove" refers to the individual kind of trees. Aubreville (1970) defined mangroves as "the coastal tropical formations, found along the border of the sea and lagoons, reaching up to the edges of the river to the point where the water is saline, growing in swampy soil and covered by sea water during high tides." Geriech (1973) defined mangroves as "trees of various species of several families which grow only where they come into permanent contact with sea water or brackish water." Blasco (1975) said "The Mangrove is a type of coastal woody vegetation that fringes muddy saline shores and estuaries in tropical and sub-tropical regions." Arroyo (1977) defined the mangroves as "A small group of tree mangrove plants and associated species belonging to systematically unrelated families, possessing similar physiological characteristics and structural adaptations with common preference to the intertidal habitat." Clough (1982) defined mangroves as "Mangroves are the only trees amongst relatively small group of higher plants those have been remarkably successful in colonising the intertidal zone at the interphase between land and sea." Naskar and Guha Bakshi (1987) defined mangroves as "Coastal tropical forest formations encircled or spread by the tidal rivers and/sea water, flooded frequently by the tidal water."

Mangroves are assemblages of salt-tolerant trees and shrubs that grow in the intertidal regions of tropical and subtropical coastlines. They grow luxuriantly in the intertidal silted up deltaic regions, estuarine mouth sheltered shallow coasts, edges of the island and saline mud flats where freshwater mixes with seawater and where sediment is composed of accumulated deposits of mud.

1.3 Global Distribution of Mangroves

Mangroves are distributed around the equator in tropical and subtropical regions largely between 5°N and 5°S (Giri et al. 2011), although there are some exceptions in Bermuda (32°N), Japan (31°N), South Africa (32°S), Australia and New Zealand (38°S) (Fig. 1.1). Mangroves are mostly distributed over 124 countries and territories in the tropical and subtropical regions (Fig. 1.1). Asia has the largest extent of the world's mangroves. About 40% of the world's mangrove cover is found in Southeast Asia and South Asia followed by South America, North Central America and West and Central Africa. India has about 3% of the total mangrove cover in the world comprising 4975 km^2 (FSI 2019).

The actual coverage of world mangroves is debated with different mangrove experts projecting different mangrove forest areas. Global coverage has been variously estimated at ten million ha (Bunt et al. 1982), 14–15 million hectares (FAO 2007; Finlayson and Moser 1971; Schwamborn and Saint-Paul 1996) and 24 million ha (Twilley et al. 1992). Spalding et al. (2010) pegged mangrove area at 152,361 km^2, slightly less than the FAO estimate. Based on the first full assessment of all mangrove forests of the world, Giri et al. (2011) estimated that the total mangrove forest area of the world in 2000 (corrections added by them in September 2010 after first online publication) was 137,760 km^2 in 118 countries and territories, whereas Hamilton and Casey (2016) using a higher spatial scale gave a total of 83,495 km^2 in 105 countries.

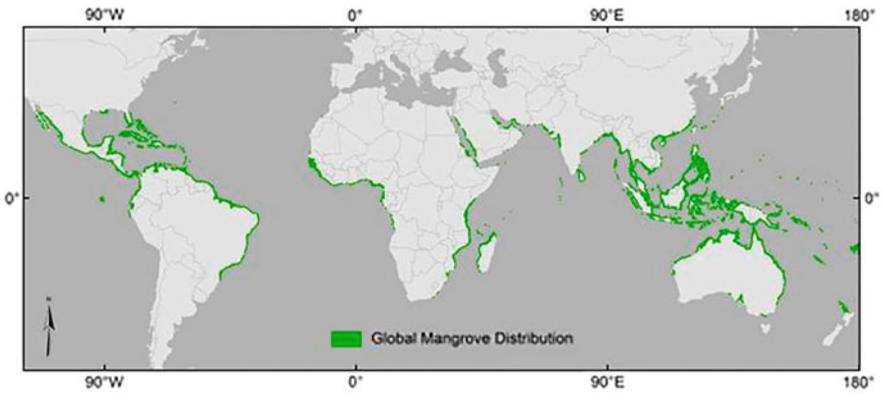

Fig. 1.1 Global Distribution of Mangrove. (Source: Cárdenas et al. 2017)

Table 1.1 Worldwide Area of Mangroves by Region (Source: Spalding et al. 2010)

Region	Area (km^2)	Percentage of total
North and Central America	22,402	14.7
South America	23,882	15.7
East and South Africa	7917	5.2
Central and West Africa	20,040	13.2
Middle East	624	0.4
East Asia	215	0.1
Southeast Asia	51,049	33.5
South Asia	10,344	6.8
Australasia	10,171	6.7
Pacific Ocean	5717	3.7
Total	**152,361**	**100**

However, there is consensus that the most extensive and highly developed mangrove forests and where the flora is rich both in quantity and in quality are found in the Indo-Malayan region and particularly in the islands of Kalimantan where the configuration of the country favours the formation of mangrove swamps over large areas in the coastal region. Indonesia contains the largest area of mangrove forest in the world. More than three million hectares of mangrove forests grow along Indonesia's 95,000 km coastline, 20% of all mangrove ecosystems in the world (Giri et al. 2011). The largest extent of mangroves occurred in Asia (42%) followed by Africa (20%), North and Central America (15%), Oceania (12%) and South America (11%) with approximately 75% of mangroves concentrated in 15 countries (Giri et al. 2011), with 50% in Indonesia, Brazil, Malaysia and Papua New Guinea (Hamilton and Casey 2016) (Tables 1.1 and 1.2).

1.4 Mangroves: A Unique Ecosystem

Mangrove is a unique ecosystem. It is formed in the inter-tidal areas at the confluence of rivers and seas. The tidal environment and waterlogged soil with often dense anaerobic mud mean the trees have adapted to survive and the most striking is the development of superficial rooting systems (Fig. 1.2). The rooting system aids in anchoring and aiding in respiration in the largely anoxic surroundings. The laterally spreading subsurface cable and anchor roots give mechanical support to the tree, while the nutritive fine roots serve for nutrition and for the assimilation of oxygen from the uppermost silt layer. The rooting adaptations of mangroves include surface roots, stilt roots, various types of pneumatophores and various types of aerial roots. Mangrove species usually possess numerous lenticels covering the stem and the roots, aiding in respiration. When the lenticels are covered by the tide, root pressure begins to drop. When the tide goes down, air is again sucked into the aerenchyma. The thick and succulent leaves also enable the plant to withstand water stress, and

Table 1.2 Recent Area of Mangroves in the 15 Most Mangrove-Rich Countries

Region	Country	Area (km^2) Giri et al. (2011)	Area (km^2) Spalding et al. (2010)	(%)
Palaeotropics	Indonesia	31,139	31,894	20.9
	Australia	9780	9910	6.5
	Malaysia	5054	7097	4.7
	Myanmar	4946	5029	3.3
	Papua New Guinea	4801	4265	2.6
	Bangladesh	4366	4951	3.2
	India	3683	4326	2.8
	Madagascar	2781	–	–
	Philippines	2631	–	–
	Nigeria	6537	7356	4.8
	Guinea Bissau	3387	–	–
	Mozambique	3189	–	–
Neotropics	Brazil	9627	13,000	8.5
	Mexico	7419	7701	5.0
	Cuba	4215	4944	3.3
	Columbia	–	4079	2.7

Source: Giri et al. (2011) and Spalding et al. (2010). Percent of total area is derived from Spalding et al. (2010)

through the transpiration process, excess salt is released as epidermal secretions which in turn are washed out by rain or evaporated into the humid atmosphere.

The structural complexities of the mangrove vegetation create a unique environment which provides ecological niches for a wide variety of organisms both marine and terrestrial. Mangroves form the foundation of a highly productive and biologically rich ecosystem which provides a home and feeding ground for a wide range of species, many of which are endangered (Duke et al. 2014) species such as the Royal Bengal Tiger (*Panthera tigris*), Saltwater Crocodile (*Crocodylus porosus*), Fishing Cat (*Prionailurus viverrinus*), Gangetic Dolphin (*Platanista gangetica*), Irrawaddy Dolphin (*Orcaella brevirostris),* Goliath Heron (*Ardea goliath*) and Water monitor lizard (*Varanus salvator*). The mangroves also serve as nurseries to shellfish and finfishes that sustain coastal commercial fisheries and local communities.

1.5 Significance of Mangroves

Mangroves only make up less than 1% of all tropical forests worldwide, but they are highly valuable ecosystems, providing an array of essential goods and services which contribute significantly to the livelihoods, well-being and security of coastal communities. The complex network of mangrove roots can help reduce wave energy, limiting erosion and shielding coastal communities from the destructive

Fig. 1.2 *Rhizophora mucronata* with its unique stilt roots in tidal ecosystem

forces of tropical storms. Mangrove ecosystems are often an essential source of seafood for both subsistence consumption and the local and national seafood trade, in addition to providing other materials such as firewood and timber, which support the livelihoods of thousands of coastal communities. Beyond their direct benefits, mangroves also play an important role in global climate regulation. On average, they store around 1000 tonnes of carbon per hectare in their biomass and underlying soil, making them some of the most carbon-rich ecosystems on the planet.

Despite its value, the mangrove ecosystem is one of the most threatened on the planet. Mangroves are being destroyed at rates 3–5 times greater than average rates of forest loss, and over a quarter of the original mangrove cover has already disappeared, driven by land conversion for aquaculture and agriculture, coastal development, pollution and overexploitation of mangrove resources (Duke et al. 2014). As mangroves become smaller and more fragmented, important ecosystem goods and services will be diminished or lost. The consequences of further mangrove degradation will be particularly severe for the well-being of coastal communities in developing countries, especially where people rely heavily on mangrove goods and services for their daily subsistence and livelihoods.

However, the future of mangroves does not have to be bleak. Increasing recognition of the importance of mangrove ecosystems for both biodiversity and human well-being is driving efforts around the world to conserve, better manage and restore these ecosystems. Many of these have been successful at a local scale, often supported by national policies that recognise the significant long-term benefits of mangroves over short-term financial gains. Mangroves need to be understood for the valuable socio-economic and ecological resource they are, and conserved and managed sustainably. This will take a commitment by governments to make policy decisions and enforce existing protection measures to curb the widespread losses from human activities. This global synthesis document serves as a call to action to decision-makers and highlights the unique range of values of mangroves to people around the world. It aims to provide a science-based synthesis of the different types of goods and services provided by mangroves and the associated risks in losing these services in the face of ongoing global habitat loss and degradation. The document provides management and policy options at the local, regional and global level with the aim of preventing further losses through effective conservation measures, sustainable management and successful restoration of previously damaged mangrove areas. Our hope is that this call to action will generate renewed interest in mangroves for policymakers, helping to safeguard the future for these essential yet undervalued ecosystems (Table 1.3).

Table 1.3 Summary of significance of Mangroves

Local level	Global level
It is the interface between terrestrial forests and aquatic marine ecosystems, an important ecosystem supporting local biodiversity and livelihoods	Unique ecosystem of estuarine forests, wetland and waterbodies providing habitat for wide biodiversity of flora and fauna some globally endangered and threatened
Mangroves provide fuelwood and firewood, charcoal, and medicinal and other uses for local communities	Important socio-economic and cultural goods and services provided by mangroves
Mangroves serve as nurseries to shellfish and finfishes and sustain the coastal fisheries and coastal livelihoods	Mangroves serve as breeding, feeding and nursery grounds for most of the commercial fishes and crustaceans on which thousands of people depend for their livelihood
Mangrove forests act as natural "bio-shield;" the presence of dense mangrove forests reduces the speed of cyclonic storms coming from seas and thereby protects villages from extreme damage, tidal surges and seawater intrusion	Mangroves act as shock absorbers. They provide protection to the coastline and minimise disasters due to cyclones and tsunamis
Roots bind silts and soils, hence reducing soil erosion and loss of important local land	Roots reduce high tides and waves and help prevent soil erosion by trapping debris and silt and stabilise the near-shore environment. This will become more important with global climate change and increasing sea-level rises

(continued)

Table 1.3 (continued)

Local level	Global level
Maintains "Bio-geo-chemical" cycles, thereby increasing planktonic population (phytoplanktons and zooplanktons)	Mangroves perform important ecological functions like nutrient cycling
Certain mangrove species act as bio-filters as they have been found to bio-accumulate heavy metals and help with pollution in coastal waters	Mangroves perform important hydrological functions and services. They filter groundwater and storm water run-off which often contains harmful pesticides. They recharge the groundwater by collecting rainwater and slowly releasing it to the underground reservoir
	Mangroves are an important global carbon sink by absorbing CO_2 (carbon sequestration @0.06 to 0.12 g carbon/m^2/day); they can help with climate change

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Chapter 2
Mangrove Forests and Silviculture

Sudhir Chandra Das

Abstract Mangroves are threatened coastal, intertidal, halophytic plants that play very important roles in the sea–land interface areas and deltaic ecosystems of both tropical and subtropical zones. Mangroves are especially significant in the highly populated Southeast Asian countries, several Pacific Islands, and Australian coasts constituting Old-World Tropics. They are also found in South America, Mexico, and West African Coasts constituting New World Tropics. All the genera of mangroves have closely related characteristics but belong to distantly related families. Most of the species possess remarkable and highly specialized adaptations like stilt roots, knee roots, ribbon roots, pneumatophores, vivipary, and xerophyllous foliage. The silviculture of a few important species is mentioned, which can aid identification and future mangrove restoration projects.

Keywords Mangroves · Halophytic · Pneumatophores · Stilt roots · Vivipary · Estuary

2.1 Introduction

The term "Mangrove" applies to a specially adapted vegetation of the littoral region of the world, which is confined mainly to the tropics and in favorable localities extends into the subtropical zone. Mangrove forests cover extensive tracts of swampy land along the tropical seas, always fringing muddy saltwater creeks, lagoons, and estuary of rivers and on low islands. They form a characteristic dense, evergreen, and impenetrable mass of trees with numerous arched branching roots. The mangrove belt occupies a strip of low-lying muddy ground, subject to periodical inundation by tides. These forests develop on fresh alluvial deposits between the high and low tide limits and stop sharply beyond the influence of saltwater. The mangrove vegetation is of a transitory nature and represents only a seral type, condition of growth change with the progress of siltation and elevation of

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the land from sea level. The species occurring in mangroves exhibit certain pronounced characteristics for their peculiar manner of growth and seeding and possess remarkable specialized adaptations, such as aerial roots and vivipary, which enable them to exist in such habitats.

Mangrove forests are mostly tropical, with some excursions into subtropical regions such as Florida, South Africa, Victoria Australia, and southern Japan where warm tropical currents transport propagules (Tomlinson 1986). Mangroves occur worldwide in the tropics and subtropics, mainly between latitudes 25°N and 25°S. There are two broad major mangrove regions of the world distinguishable: the Old-World Tropics, Eastern or the Indo-Pacific type consisting of eastern coast of Africa, Asia, Australia, and the islands of Indian and Pacific Oceans, and the New World Tropics, Western or Atlantic type comprising of the coasts of North and South America, Western Africa, West Indies, and other Atlantic Islands.

The species occurring in the respective areas are distinct, but the eastern area is far richer in species than the western. The Indo-West Pacific Tropical Zones and Tropical Australia have the most dominant mangroves and are important in respect of species diversity, richness of the mangroves, abundance, and unique succession features of the mangroves. The flora of the mangrove forests of the eastern type (Indo-West Pacific region) consists of about 63 species with Rhizophoraceae predominating, whereas the western type (Atlantic coasts of Americas and Africa) consists of 16 species only (Chapman 1970).

All the genera of Mangroves have closely related characteristics but belong to distantly related families. Rhizophoraceae are most typical. Shrubs are few, *Acanthus* being the commonest, while the fern *Acrostichum aureum* is very typical. Palms are similarly limited to a few species notably *Phoenix paludosa* and *Nypa fruticans*. Grasses are commonly absent, but *Oryza coarctata* is an early colonizer. The silvicultural characters of all mangrove forests are remarkably identical.

2.2 Site Factors for Mangroves

The mangrove forests develop along the sea coast on fresh alluvial deposits between low and high tide limits. As a rule, the soil is clayey of considerable depth occasionally with a small admixture of sand blown by wind or deposited by water. In consistency, it varies from a semi-fluid mud to heavy stiff clay depending upon the frequency and duration of inundation. Waterlogging with saline water is a common feature, and aeration is poor. The saline nature of the soil moisture renders the sites physiologically dry.

The natural habitat of the trees is characterized by a tropical coastal climate, moist, warm, and equable with no perceptible division into pronounced seasons. Due to proximity to sea, humidity is uniformly high (75–80%) throughout the year. The temperature varies little throughout the year; mean annual temperature is very close to 27 °C with maximum of 30 °C and minimum of 22 °C. The habitat is generally sheltered against the strong wind and sea waves.

There are some extreme distributions such as *Avicennia* occurring at 38°45′S in Australia, and this may be due to local anomalies of current and temperature (Hogarth 1999).

2.3 Species Distribution

The divergence of mangrove plant species between old and new world mangroves has been explained by geological events (Duke 1995; Spalding et al. 2010). Species richness of different mangrove regions is depicted in Table 2.1.

2.4 Classification of Mangroves

Mangroves and mangrove associates have been variously categorized by different authors. Tomlinson (1986) has categorized them into (1) major elements of mangroves, (2) minor elements of mangroves, and (3) back mangroves or mangrove associates. Mepham and Mepham (1984) pointed out that there may be some physiological races existing in these mangrove species as they have different abilities to tolerate salt upon different populations. They have suggested that based on the salinity in their habitats, mangrove should be termed as freshwater mangroves and saline water mangroves.

Blasco (1975) identified the following 5 species compositions in his classification: (1) back mangroves (euryhaline zone) found on the river bank; (2) dense mangrove consisting of many species of plants; (3) tall, dense trees of *Heritiera fomes* with primary associate *Excoecaria agallocha*; (4) brackish water of mixed *Heritiera fomes* forests with *Rhizophora* species over a very limited area; and (5) palm swamps consisting of pure *Phoenix paludosa*. Naskar and Guha Bakshi

Table 2.1 Distribution of some principal mangrove species by region

Family	Species	America and W Africa	E Africa to Asia/Australia
Avicenniaceae	*Avicennia*	3 species	5 species
Combretaceae	*Laguncularia*	1 species	0
	Lumnitzera	0	2 species
Rhizophoraceae	*Bruguiera*	0	6 species
	Ceriops	0	2 species
	Kandelia	0	1 species
	Rhizophora	3 species	6 species
Sonneratiaceae	*Sonneratia*	0	5 species
Palmae	*Nypa*	0	1 species
Plumbaginaceae	*Aegialitis*	0	2 species
Myrsinaceae	*Aegiceras*	0	2 species

(1982) grouped mangrove forest into five major zones as follows: (1) sea face of beach forest; (2) formative island flora; (3) flora of reclaimed land and low-lying area; (4) flora of river banks; and (5) swamp forest.

The total plant species are grouped into 59 families, 101 genera, and 140 species. These comprise true mangroves or major elements, minor elements of mangroves or/and mangrove associates, back mangrove trees and shrubs, non-halophytic non-mangrove associates in the area, halophytic herbs, shrubs, and weeds and epiphytic and parasitic plants.

2.5 Characteristic Features of Mangrove Flora

Mangrove plants are salt-loving or halophytic plants, which show numerous modifications and adaptations in order to survive in the anoxic, waterlogged saline soils:

- Extensive lateral root systems for a proper anchorage against diurnal tidal inundation/scouring, e.g., *Excoecaria* sp.
- Supporting roots like stilt roots or prop roots. Root buttresses are formed in species like *Rhizophora* and *Xylocarpus.* Vertical knee roots from horizontal lateral roots are given out by species like *Lumnitzera, Bruguiera gymnorrhiza*, and *Kandelia candel.*
- To facilitate gaseous exchange as the lateral roots get submerged due to tidal movement, breathing roots or "pneumataphores" have been developed. These roots grow above the earth surface and contain pores called lenticels through which gaseous exchange occurs. In addition to pneumatophores, even the stilt roots contain lenticels as seen in the case of *Rhizophora mucronata*.
- To counter the excess saline conditions outside the plant cells, very high osmotic pressure is exerted in order to draw water from outside salt solution. It has been seen that the cell sap is rich in organic electrolytes in case of *Rhizophora* sp. and inorganic electrolytes in case of *Suaeda* sp.
- The leaves are normally thick and often contain salt excretory channels to deposit crystals and waxes of various compositions on leaves. Salt hairs on leaves of *Porteresia coarctata* burst to excrete salt. *Avicennia alba*, *Acanthus ilicifolius*, *Aegialitis rotundifolia*, and *Aegiceras corniculatum* also show salt excretory mechanisms.
- Mangrove leaves have sunken stomata to prevent water loss.
- The fruits of *Rhizophora, Bruguiera,* etc., germinate right on the tree and fall like a dart on the mudflats to get anchored against tidal inundation. This phenomenon is called as "Vivipary" and is an adaptation unique to mangrove plants.

Mangroves have also started manifesting quaint adaptations (being out of normal domain), as is the case of *Avicennia* species, which never throw stilt roots and are an outer estuarine species, but, when found in the mid-estuarine creeks at the foreshore, give rise to stilt pneumatophores in order to combat the higher velocity and undermining effect of water. Both stilt roots and normal pneumatophores of

Avicennia are histologically alike and contain chlorophyll unlike other stilt-rooted mangroves. Some species like *Excoecaria agallocha* (an inner estuarine species), which normally does not have pneumatophores or stilt roots, give rise to perforated "Burr" formations on the lower stem in order to ensure gaseous exchanges at places where tidal amplitude is more severe, i.e., the mid-estuarine environment. Thus, the mangroves exhibit a unique pattern of species movement. The species of the tidal forests are endowed by nature with a number of highly specialized adaptations**,** to withstand the very exacting combination of site factors they have to contend with.

2.5.1 Root Systems

The root system of the mangroves is highly specialized due to defective soil aeration they have developed devices to combat this. In the case of *Rhizophora*, the lower part of the stem dies early and the stem is supported by numerous stilt roots that rise above the mud, while aerial roots are sent down from the roots and branches and anchor themselves firmly in the soft tidal mud. This ensures stability and protection against the considerable force of sea waves and wind. These stilt roots are covered by water at high tide and exposed at low tide and prevent soil erosion by trapping sediments in the roots. *Rhizophora* is usually characteristic of the outer edge of the mangrove swamp, and the mass of stilt roots (Fig. 2.1) is a conspicuous site on approaching the shore. These peculiar stilt roots are not conspicuously developed in other species of mangroves. In other species, the roots are superficial, twisted above on the surface of the mud as in case of *Xylocarpus granatum* and sometimes bending out of the mud in the form of knees (knee roots) as in *Heritiera*, *Bruguiera*, *Kandelia*, and *Lumnitzera*. Some species produce lateral branches, known as pneumatophores, which arise from the superficial horizontal roots and emerge above the mud here and there resembling inverted tent pegs as in *Sonneratia*, *Xylocarpus*, *Avicennia,* and *Ceriops*. The ribbon roots, knee roots, and vertical pneumatophores are all adaptations for supplying the roots with oxygen and are covered with lenticels for breathing purposes (Fig. 2.1).

2.5.2 Leaf Structure

The habitat of the mangroves, namely swampy grounds impregnated with salts, is a physiologically dry one and the leaves of the trees possess a marked xerophilous structure, which helps them against the conditions of physiological droughts created by saline soil and the factors favoring rapid transpiration. The leaf structure is marked by a thick cuticle, large mucilage cells, sunken stomata, and a large-celled, thin-walled aqueous tissue, the dimension of which increases with the age of the leaves and with corresponding rise in salt content. Old leaves serve essentially as

Fig. 2.1 Different root system of Mangroves (Top left—Pneumatophores of *Xylocarpus*, Top right—Pencil roots of *Avicennia*, Bottom left—Stilt roots of *Rhizophora*, Bottom right—Knee-roots of *Bruguiera*)

water reservoirs for the young leaves. They are also characterized by high osmotic value relations.

2.5.3 Germination

Nearly all the mangrove species exhibit the most interesting characteristics of vivipary or semi-vivipary (Joshi 1984). The germination of the seeds and partial development of the embryo take place, while the fruit is still upon the tree and thus makes considerable growth before the fruits fall vertically so that on falling the radicle gets embedded into the mud. Vivipary is more pronouncedly exhibited in Rhizophoraceae and some other genera belonging to Myrsinaceae and Verbenaceae. The fruit is indehiscent, and there is no resting stage for the embryo as is the case of normal seeds. As soon as the fruit is fully developed, the embryo commences to grow inside it; the radicle soon pierces its apex and the hypocotyl elongates and protrudes hanging vertically from the fruit. After it has reached a length varying from a few centimeters to 45–60 cm or more as in the case of *Rhizophora mucronata*, the embryo plant falls leaving the cotyledons inside the fruit that remains on the tree.

The lower part of the hypocotyl is thicker than the upper part, and in some cases, the lower extremity (radicle) comes to a sharp point; when the embryo falls into the mud, it therefore becomes firmly planted in a more or less vertical position. Within a short time of falling, the young seedling produces rootlets from its lower extremity, thus further establishing itself. The embryos are buoyant, and if they do not obtain an immediate footing under the parent tree or they are uprooted, they are carried away by water and find a resting place in the mud, eventually establishing themselves in an upright position through the positive geotropism of the lower extremity and the negative geotropic nature in the upper extremity (shoot).

In silviculture term, sowing or dibbling of mangrove seeds is strictly speaking incorrectly; it is the embryo or young seedlings, which are planted in the ground. Rapid rooting and growth of pre-seedling in the early stages are common to all tidal viviparous and non-viviparous species. The mangrove species generally have a strong gregarious habit and tend to occur in more or less pure patches. They are a strong light demander, although they are shade-tolerant in the early stages.

2.6 Silviculture of Some Important Mangroves

Silviculture is the practice of controlling the regeneration, growth, composition, and quality of forests to meet values and needs. Forest management involves the integration of silvicultural practices with the concepts of social and political aspects of sustainable forestry. In this section, we will discuss ten (10) important mangrove Genera belonging to the families—Sterculiaceae (*Heritiera*), Verbenaceae (*Avicennia*), Rhizophoraceae (*Rhizophora, Ceriops, Bruguiera,* and *Kandelia*), Sonneratiaceae (*Sonneratia*), Euphorbiaceae (*Exoecaria*), Myrsinaceae (*Aegiceras*), and Arecaceae (*Nypa fruticans*), which have characteristic features and prevalent in many regions. Rhizophoraceae is the largest family of mangroves so more than one important genus is selected to highlight their silvicultural characteristics. The details of fruiting and flowering are from authors' own experiences in India and may differ in some other regions.

2.6.1 Heritiera fomes *Buch. Ham. Syn.* Heritiera minor *Lam. Family: Sterculiaceae*

Heritiera is known as Sundari in the Sundarbans and in Orissa, India. It is abundant in the deltaic regions of the Ganges, Brahmaputra, and Mahanadi ascending up the rivers within tidal limits and along the coast of eastern peninsula. It reaches its best development in Myanmar in the tidal forests from Arakan to Tenasserim. Though its habitat is situated south of the Tropic of Cancer, the temperature is equable due to its proximity to the sea with high rainfall. The tree is found growing from the sea and extends inland but not far; a certain amount of salt is indispensable for its growth, but excess is harmful. It does not flourish on high ground where salt concentration is very high. It thrives well on a low-lying, moist, clayey loam, with a slight admixture of salt. However, on very wet soils and on saline high banks its growth is stunted. *Heritiera fomes* is a characteristic species of Tidal Swamp forests in saltwater mixed *Heritiera* forests and in brackishwater mixed *Heritiera* forests. In saltwater mixed *Heritiera* forests, it occurs in association with *Exoecaria agallocha, Ceriops roxburghiana, Bruguiera conjugata, Avicennia officinalis,* and *Xylocarpus moluccensis*. In brackishwater mixed *Heritiera* forests, it occurs in association with *Bruguiera conjugata, Avicennia officinalis, Xylocarpus moluccensis, Sonneratia apetala,* and *S. caseolaris*. The freshwater type of *Heritiera* forest is mostly found in Bangladesh, and only the saltwater type is found in Indian Sundarbans.

It is a medium-to-large evergreen tree, often grooved and buttressed, 15–20 m in height, and 1–1.8 m in girth in favorable localities. The trees grow in close crops, so it is seldom found with branches low down. The crowns of individual trees are light, but their combination forms close canopy. The root system of the species is not deep. A peculiarity of this species is that it sends up pneumatophores copiously, which serves as respiratory organs. Some have knobs and knees on the surface of the ground, but all have numerous lenticels. The species is easily recognized by these aerial roots. Bark is dark gray with longitudinal fissures. Aerial roots are flat on either side. In the estuarine areas, they are so close that it is difficult to step in. Leaves measure 10–15 × 4–5 cm, oblong, lanceolate, petiolate, and leathery with silvery scales beneath. Leaves are simple and alternate. Flowers are small, orange-colored, and unisexual in tomentose panicles. Fruits are 3–4 cm in diameter, woody, indehiscent shining capsules, keeled, and capable of floating on the sea water (Fig. 2.2).

The trees flower from April to June and fruits are available from August to September. Both flowering and fruiting take place later in the saltwater areas than in the freshwater areas. Flowers are much more numerous on the trees growing on the river banks projecting over the streams so that seed dispersal by water will be easier. Seeds being buoyant are borne along in quantities on the surface by tidal currents until stranded. Germination is hypogeous and takes place very soon after the carpels fall. The thick fleshy cotyledons remain within the fibrous wall of the carpel; the stout radicle appears first, the petioles of the cotyledons meanwhile elongating so as to enable the plumule to emerge; latter soon appears the young shoot elongating and arching until stationed.

The tree is a moderate light demander. It can withstand fairly heavy shade in early stage, but once it is established, it responds well to a partial removal of shade. The distribution of the species in the Gangetic Delta clearly bears out its preference for supply of freshwater. The coppicing power of the species varies considerably, and it is usually a poor coppicer. For successful coppice growth, abundance light is required. It pollards well.

Natural regeneration is excellent in most localities in its habitat. The species bears fruit annually but plentiful seeds occur only at intervals. Germination begins while the seeds are floating on the water. Natural regeneration is satisfactory where fresh

Fig. 2.2 *Heritiera fomes* tree, flowering stage and fruiting stage

deposits of silt are observed. In the area where natural regeneration fails, artificial regeneration is attempted. For artificial regeneration, seed sowing in situ would have to be secured to prevent its floating away at high tide. Judicious thinning in increasing the rate of growth of the trees is found successful. The selection system is the suitable silvicultural system for the management of *Heritiera* forests. Felling cycle may be fixed at 20 years, and exploitable diameter may be 7.5 cm. It is very hard due to interlocked grains, elastic, strong, and heavy. It is excellent firewood. It yields charcoal of good quality and is suitable for gun powder. A transparent gum obtained from the bark is used medicinally and also as an adhesive.

2.6.2 Heritiera littoralis *Dry. Family: Sterculiaceae*

It is called Sundari in Bengali, Sundrichand in Marathi, and Sundari in Andaman also. It is also called looking-glass tree, the Red Mangrove of Queensland. It is a small- to medium-sized evergreen ornamental tree. It exhibits characteristic thin curving buttresses. It grows gregariously in the tidal forests all along the seashore in Andaman, Sundarbans, and east and west coasts of peninsular India. It is also widely distributed along the sea coasts in the Malayan region, Philippines, and Java. It occurs in the Littoral and swamp forests (sub-group 4A and sub-type 4A/L1 as per Champion and Seth 1968) in association with *Barringtonia asiatica, Erythrina variegata, Pongamia pinnata, Casuarina equisetifolia, Calophyllum inophyllum*, and *Terminalia catappa* and in brackish water mixed *Heritiera* forest (sub-type 4B/TS4) in association with *Barringtonia racemosa* and *B. asiatica*.

It's bark gray or discolored, and longitudinally furrowed. Leaves are elliptic-oblong, acute, or obtuse, glabrous above, and lower portion is covered with minute, silvery scales; base is rounded or acute, petiolate. Flowers are small, orange, or greenish pink in tomentose drooping axillary panicles in the upper axils. Fruits are ripe carpels, thick, and woody having sharp keel or wing. Seeds are 2.5 cm long. Both flowering and fruiting take place in the rainy season. The wood is hard, tough, elastic, strong and heavy, knotty, and twisted. It is mainly used in building boats, posts, poles, joists, tool handles, etc. The seeds are edible and used as adulterants for cola nuts. The bark contains 15% tannins and is used in Philippines for toughening fishing nets.

2.6.3 Avicennia officinalis *L. Syn.* A. tomentosa *Wall. Family: Verbenaceae*

Avicennia officinalis is commonly known as white Mangrove or Bain in Sundarbans and is found from India across Asia to Papua New Guinea. It is a large evergreen shrub or small tree of the mangrove swamps (Fig. 2.3). It is one of the commonest of the Indian mangrove swamp species, especially in east and west coasts of Indian Peninsula growing gregariously and often forming an extensive bushy growth, conspicuous from its gray foliage, and bright yellow inflorescences when in flowering condition. Its lateral roots spread in all direction through the soft mud and send up slender vertical pneumatophores. In the Sundarbans, it occurs in the inland parts of the littoral forest and is characteristic of moist depressions.

Fig. 2.3 *Avicennia officinalis* tree with its flowering stage

The wood has a peculiar structure consisting of alternate layers of pore-bearing tissue and loose large-celled tissue without pores. It is brittle and is used only as fuel, but in some localities, it is an important fuel species. The panicle heads of yellow flowers appear from March to June, and the fruits ripen from August to October. The fruit is a compressed ovoid one-seeded capsule, 2.5–3.5 cm long, dehiscing into two thick valves. The large fleshy cotyledons fill the fruit. The seeds often germinate on the tree or immediately after falling. Thick, densely hairy hypocotyls elongate from the lower end and of which a number of rootlets appear and the shoot is produced from its upper end. The seeds are buoyant and are thus able to spread by the agency of water; about October, the tidal creeks are often full of large seeds floating on the surface of the water and most of the seeds will be found to be germinating. The best method to collect the seeds for artificial regeneration is to drag with a small net and throw the seeds into a boat partly filled with water, which should then proceed straight to where the seed is to be sown. The seeds should be sown immediately after collection without delay. Usually, the seeds are broadcasted between new moon and full moon when the tides are lowest; the sowing is done when the tide has run out, and there is no water on the ground; otherwise, there is danger of the seeds floating away (Wood 1902).

Under favorable conditions, the saplings regenerate freely from seeds. The necessary conditions appear to be frequent flooding and absence of dense low cover, which the seedlings do not tolerate. Thus, a lowering of the water level results in a cessation of reproduction, while a dense growth of *Acanthus ilicifolius* tends to kill out the seedlings. The tree does not coppice well. Its lateral roots spread in all directions through the mud in which it grows and sends up plentiful pneumatophores. *Avicennia* plants are the pioneer species of the muddy flats and pave the way for other species depending upon the silting activities and rise in the level of the mudflat by further accretion.

2.6.4 **Rhizophora mucronata** ***Lam. Family: Rhizophoraceae***

It occurs on the East Coast of Africa and Madagascar to the Indian Peninsula, Andaman Islands across Asia and North Coast of Australia. It is a small- to moderate-sized evergreen tree, with many branches attaining a height of 7.5 to 12 m and a girth of 0.5–1.0 m with elliptical mucronate leaves 10–15 cm long, and the young branches are thick and prominently marked with the scars of fallen leaves and stipules. Bark is fairly smooth and brown. This tree produces characteristic stilt roots, the lower portion of the stem dying early, and the tree remaining propped up on numerous roots, which are submerged at high tide and stand out of the mud at low tide. Aerial roots are also produced from the branches, and these fix themselves in the mud. This tree is most commonly found on the outer fringes of the mangrove swamp where water is salty, and the action of the tides and waves is most strongly felt; its peculiar root system is therefore of special advantage in forming an anchorage to withstand this action.

The conspicuous white flowers appear in the hot season and the rainy season from April to September, and the fruits ripen in late rainy season from July to October. The fruit is 4–5 cm long, conical-ovoid, pendulous, coriaceous, rough, and dark brown. The hypocotyl, which emerges through the apex of the fruit, is sharp-pointed and rough with lenticels. Before dropping, it attains a considerable length (up to 45–60 cm) but sometimes longer and the seedling is thus able to establish itself in water of some little depth, the sharp point of the hypocotyl penetrating the mud, and the young plant being kept upright while the roots are rapidly developed and the first pair of leaves appear at the apex of the shoot. Seedlings that have established themselves in this way may often be found in quantity in the mud and shallow water round the parent trees. The tree commences to produce fruits at an early age. It is a poor coppicer. Natural regeneration of the species comes up fairly well throughout its habitat, and the trees are not known to have been raised artificially. The sapwood is light red, and the heartwood is dark red and hard but splits in seasoning. It is a good fuel. The bark is used for tanning.

2.6.5 Rhizophora apiculata *Blume Syn.* R. conjugata *L. Family: Rhizophoraceae*

This is a tree as large as *R. mucronata* with similar habits and is commonly associated with it in its habitat. Bark is gray, smooth, with shallow vertical furrows or short horizontal fissures. Leaves are lanceolate, cymes are two-flowered, and petals are thin and glabrous. The leaves are narrower and darker than in *R. mucronata,* and it can be easily distinguished by its calyx–lobes, which are pale yellow within (Fig. 2.4). The fruit is about 2.5 cm long; hypocotyl is smaller, about 30 cm long. It produces seeds abundantly with germination capacity of about 70–75%.

2.6.6 Ceriops decandra *Griff. Syn,* C. roxburghiana *Arn., and* Ceriops tagal *(Perr.) C.B. Robs. Family: Rhizophoraceae*

Ceriops spp. are small evergreen trees, and the 2 species resemble each other in appearance and habit and are distinguished mainly by the inflorescence, which is more compact in the later than in the former (Fig. 2.5). The bark of both species contains a great deal of coloring matter. The stem is not supported by stilt roots as in *Rhizophora,* but aerial roots are sent down from the branches and small or inconspicuous pneumatophores are produced. The fruits (2.5–3 cm long) ripen in August–September, and the hypocotyl, when it falls, is 10–15 cm long by 0.5–0.7 cm in

Fig. 2.4 *Rhizophora apiculata* tree with stilt root and its vivipary fruiting

Fig. 2.5 *Ceriops decandra* tree and its flowering stage

diameter, longitudinally grooved, and ribbed, tapering upward. 250–300 of the embryos weigh about 1 kg.

Both are indiscriminately known in the Sundarban as Goran and are in great demand for fuel and house posts. It is often gregarious forming nearly pure forests in many places; it is also found in mixtures with various other species. In Chittagong, Bangladesh, *Ceriops* is worked as a coppice on a rotation of 8 years for the production of fuel wood and bark. The bark is sold to fishermen for tanning their nets. In the Malay region, the bark is considered superior to that of any other mangrove for cutch making. It is also used for dyeing a red color.

2.6.7 Bruguiera gymnorhiza *Lam. Family: Rhizophoraceae*

Bruguiera gymnorhiza is one of the largest evergreen trees in mangrove forests attaining a height of up to 30 m and a girth of 1.5–1.8 m in Malaysia (Fig. 2.6), but in India, it attains only a height of 10–12 m. It occurs on the tidal mud banks in the deltaic region of rivers, which are permanently wet with saltwater and submerged daily by every tide frequently. The tree is common in mangrove forests of Indian region and associated with the two species of *Rhizophora* and occurring immediately behind them.

Bark is rough, dark with large corky lenticular patches. Flowers are large, solitary, orange, or red. Fruits 2.5–3.0 cm long, enclosed in the calyx tube, and crowned by 12–14 red calyx lobes. The hypocotyl usually grows to 15–30 cm in length before dropping but may attain a length of 60 cm. The flowers and fruits are produced from June to October. It is not supported on stilt roots but produces knee roots along the surface of the ground. The wood is reddish-brown, very hard, used for beams, posts, planks, and firewood. The bark is sometimes used for tanning.

Fig. 2.6 *Bruguiera gymnorhiza* tree and its flowering stage

2.6.8 Bruguiera parviflora *Wight & Arn. Family: Rhizophoraceae*

A small tree is widely distributed in the mangrove formations of Eastern Hemisphere and sometimes forms pure crops in the middle of the mangrove swamp. In the Indian region, it is a small tree or a mere shrub. It is characterized by rough and dark-colored bark. The foliage is yellowish-green. The fruit is about 2.5 cm long enclosed in the enlarged calyx. The flowers and fruits appear in the rainy season. The hypocotyl is furrowed, truncated, and reached a length of 10–12 cm before falling. The tree grows on drier ground than *Rhizophora*, chiefly away from the banks of streams.

2.6.9 Sonneratia apetala *Ham. Family: Lythraceae (Recently Placed in Sonneratiaceae)*

This genus comprises trees with opposite entire thick leaves growing in the mangrove swamps of littoral regions. There are four Indian species of which two (*S. apetala* and *S. acida*) are widely distributed along the coasts and the other two species (*S. alba* and *S. griffithii*) are far more local.

Sonneratia apetala is found in the tidal forests of the coasts of India, common in Sundarbans and Myanmar and known as Tok-Keora in Sundarbans and Kambala in Myanmar. It occurs on the river deltas on flat stretches alongside the streams, on soft tidal mud submerged by every tide. This is one of the chief constituents of the mangrove formation growing gregariously and springing up in more or less pure patches, usually on new alluvial land thrown up in the form of islands or of flats in the bends of tidal rivers and estuaries.

Sonneratia apetala is a small- to moderate-sized evergreen tree with slender drooping branches and light glaucous-green foliage. Bark is black, smooth with horizontal oval lenticels. Leaves measure 5–10 cm by 2.5–4 cm, oblong-lanceolate, obtuse, thick, glabrous, light glaucous-green with short petiole. Flowers solitary or in groups of 3–5, large, articulated on pedicels; calyx is 2 cm long, tube cup-shaped, 4-lobed, and petals none (Fig. 2.7). The tree produces thin upright rather sharp pneumatophores from its superficial roots. It coppices vigorously. Wood is moderately hard, used for planking, furniture, knees of boats, and fuel wood.

Whitish flowers appear from April to June, and ripe fruits are available from September in Sundarbans. They are globose, about 1.5–2.0 cm in diameter, fleshy, and indehiscent containing several angular irregularly shaped seeds about 0.75 cm long with a hard testa (Troup 1921). The fruits are buoyant and are dispersed through water. They are also eaten by birds. After falling, they soon rot and disintegrate. 175–180 fruits weigh a kilogram, and 1 kg seeds have 50,000 to 65,000 seeds. Germination is epigeous. The testa splits at one end and the radical emerges. The hypocotyl arches and the testa are carried above ground, falling with the expansion of the cotyledons. The natural regeneration of the species is abundant, and dense

Fig. 2.7 *Sonneratia apetala* trees and its flowering and fruiting stage

masses of naturally regenerated seedlings are usually noticed. The species can also be regenerated artificially. Ripe fruits are collected, and minute seeds are segregated. The seeds are then sown in nursery beds to raise numerous seedlings. After 3 months, these seedlings can be transplanted to the tidal mudflats and the area can be regenerated.

The wood is easy to saw, work, and turn and can be finished to a smooth surface with care. It is used for house construction as planks, scantlings, door boards, and rough furniture and ribs of boats. It is good firewood; the pneumatophores are suitable as substitute for cork.

2.6.10 Sonneratia acida *L.*

It is known as Ora/Chak Keora in Sundarbans and Tabu/Tamu in Myanmar. It is a small evergreen tree with dull green foliage and black shinning lenticellate bark. It produces pneumatophores in the shape of asparagus-like rootlets emerging from the mud. It flowers from March, and seeds are available in September. This is another common species of the mangrove swamps with much wider distribution than *S. apetala*.

2.6.11 Exoecaria agallocha *L. Family: Euphorbiaceae*

Excoecaria agallocha is also called the milky mangrove, blinding tree, or poison fish tree due to its white toxic latex. It occurs on the coastal and tidal forests of both sides of Indian Peninsula, Andaman Islands, Sri Lanka, and Myanmar. It grows in Eastern Asia–southern China, Indian subcontinent, Myanmar, Thailand, Vietnam, Malaysia, Indonesia, Philippines, New Guinea, and Australia and Pacific Islands. It is found in mangrove and tidal forests and brackish areas at elevations from sea level to 100 m. Milky mangrove is an evergreen or briefly deciduous shrub or small tree growing 10–15 m tall. The bole, which branches from low down, has stilt roots. The stem has rough skin. It exudes poisonous white milk from the bark if punctured, or if the leaves are torn. Bark is gray, smooth, shining with numerous rounds, prominent lenticels. Leaf is small, wide at the middle, tip pointed, dark green in color, and turns reddish-orange at maturity before shedding (Fig. 2.8). One can easily identify the plant from a distance by this orange leaf color. The root system spreads like a spider web and mostly remains exposed. Wood is very soft, spongy. Pores are small, scanty, usually in radial lines. Medullary rays are very numerous and extremely fine.

A common tree in all parts of the Sundarbans is associated with *Ceriops* (Goran) in the western and with *Heritiera fomes* (Sundari) in the eastern forests. There are some localized threats, and there has been an overall population decline caused by coastal development throughout its range. It grows occasionally to 1.0 m in girth and 12 m in height, though generally cut for posts when of small girth. Propagation is through seeds. The species flowers from April to June and seeds are available in August–September. The species normally does not have pneumatophores or stilt roots but give rise to perforated “Burr” formations on the lower stem in order to

Fig. 2.8 *Exoecaria agallocha* tree and leaf-colour change before shedding

ensure gaseous exchanges at places where tidal amplitude is more severe, i.e., like the mid-estuarine environment. It is a useful wood for general carpentry purposes such as toys, bedsteads, and tables. The timber is white. The juice when exudes from the green bark is very poisonous. All parts of the plant are poisonous. The tree exudes a very acrid poisonous juice, particularly from the fresh cortex when cut, which raises blisters on the skin and is injurious to the eyes, hence the name "blinding tree." The latex is used as a fish poison. The white wood is soft and spongy, and certain parts of the wood are used for incense. It is mainly used for charcoal and firewood. In mangrove plantations, this species is planted for its rapid growth and strength. This tree absorbs heavy metals from environment and reduces environmental pollution.

2.6.12 **Kandelia candel** *(L.) Druce and* **Kandelia rheedii** *Wight & Arn. Family: Rhizophoraceae*

These trees are distributed in South-east Asia. The trees occur in the mangrove forests of sub-type 4B/TS2 as distinguished by Champion and Seth (1968) but are not so common as most other mangrove species and occur usually on the banks of tidal rivers. It is an evergreen shrub or small tree with spongy reddish-brown flaky bark, elliptical oblong leaves, 7.5–12.5 cm long and white flowers in axillary, pedunculate, dichotomously branched cymes. Fruits ovoid, 1.2–2.5 cm long encircled by the calyx lobes; hypocotyl is up to 35 cm long. The tree flowers and fruits all the year round in different localities. The wood is soft, close-grained, and reddish-brown. It is used only for fuel and charcoal making. The tannin-rich bark is suitable for heavy-leather tannage and for dyeing red and brown.

2.6.13 **Aegiceras corniculatum** *Blanco. Syn.* **A. majus** *Gaertn. Family: Myrsinaceae*

It is an evergreen shrub or small tree with gray bark, common in mangrove forests along tidal creeks where it is frequently gregarious (Fig. 2.9). It is found from India to Australia. It flowers from February to March, and fruits are available in August–September. As it flowers first in the Sundarbans, its honey is known to be the best in quality. This tree exhibits vivipary like the true mangroves; the seeds germinate within the pericarp of the curved horn-shaped fruit. The trees coppices well. The wood is used as fuel wood.

Fig. 2.9 *Aegiceras corniculata* grove and its flowering stage

2.6.14 Nypa fruticans *Wurmb. Family: Arecaceae*

Common name Nypa palm or mangrove palm, Golpata in Sundarbans. It is a species of palm native to the coastlines and estuarine habitats of the Indian and Pacific Oceans. It is found in India, Malaysia, and Indo-China to northern Australia. It grows well in mangrove swamps, tidal areas in deep mud, and swampy coastal low-lying areas subject to tidal inundation. Being a strong light demander, it grows best in sunny locations. Plants are only found in tidal mudflats of the moist tropics in the wild, though they have been successfully cultivated in swampy ground some distance from the sea. Nypa palm is a large, evergreen palm forming a loose clump of growth from a prostrate or subterranean stem up to 45 cm in diameter. This stem branches at intervals to form individual clumps of large, erect leaves that can each be up to 6 m long. The first flowering occurs 3–4 years after germination. There is little information on germination of this plant. It seems likely that seed germination is enhanced if the seeds are immersed in sea water for a considerable period by tidal inundation.

The plant can be tapped for its sap by the time of the second flowering. The seeds have a delicious creamy flavor when the fruits are immature. The white endosperm of immature seed is sweet and jelly-like and is consumed as a snack. The mature seeds are sometimes eaten but are very hard. A sugary sap is obtained from the inflorescence. It is not only used to make an alcoholic beverage but also used to make syrup, sugar, and vinegar, a high-valued food and important source of materials for local people, providing edible seeds and sap. The leaves are an excellent material for thatching and basket making. The leaves are far superior to and more durable than coconut (*Cocos nucifera*) thatch. The strong leaf stalks have many structural uses. The leaflets and midribs are used for manufacturing brooms, mats, and sunhats. The leaves contain up to 10% tannin. It is planted along swampy coastlines with mangroves in order to protect the shore from erosion.

2.7 Conclusions

Mangrove plants are found in the tropics and subtropics on intertidal coasts. They are a diverse and distantly related group of plant families that have closely related characteristics due to adaptations for the unique tidal mangrove environment. Most of the species possess remarkable and highly specialized adaptations like stilt roots, knee roots, ribbon roots, pneumatophores, vivipary, and xerophyllous foliage. Not only their growth rate is very slow but also their artificial regeneration is difficult. Future mangrove restoration projects require an understanding of the local mangrove species and environment. Therefore, understanding the biology, ecology, and silvicultural needs of each species can help with biodiversity and conservation of mangrove forestry management.

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Chapter 3
A Review of the Reproductive Ecology of Mangrove Plant Species

Jacob Solomon Raju Aluri

Abstract Mangrove plants have a number of different reproductive adaptations, which are reviewed in this Chapter. Mangroves can be distinguished into viviparous, crypto-viviparous, and non-viviparous groups. The viviparous group includes the genera *Bruguiera, Ceriops, Kandelia,* and *Rhizophora*; the crypto-viviparous group includes *Avicennia*, *Aegiceras,* and *Aegilitis,* and the non-viviparous group includes *Lumnitzera, Excoecaria*, *Barringtonia, Xylocarpus*, *Scyphiphora,* and *Sonneratia*. Of these, *Xylocarpus* is monoecious and *Excoecaria agallocha* is dioecious; both are obligate out-crossers. All other mangroves are hermaphroditic with mixed mating systems. *Bruguiera* spp., *Ceriops tagal*, *Xylocarpus* spp., and *E. agallocha* are obligately vector-dependent. Pollen discharge mechanisms functional in these plants are either explosive or non-explosive. Explosive pollen discharge mechanism pertains to complex and elaborate petal-stamen configuration, while non-explosive mechanism pertains to simple and unspecialized floral architecture. Explosive pollen discharge occurs in *Bruguiera* spp. and *Ceriops tagal,* while non-explosive pollen discharge or presentation occurs in all other mangroves. *Scyphiphora hydrophyllacea* has a special secondary pollen presentation mechanism. Anemophily and entomophily are functional in *Rhizophora, C. tagal,* and *E. agallocha*; melittophily and anemophily in *S. hydrophyllacea*; zoophily and anemophily in *A. corniculatum;* zoophily in *L. littorea, B. racemosa,* and *S. caseolaris*; anemophily in *S. alba* and *S. apetala*; and entomophily in *C. decandra, Bruguiera, Kandelia, Avicennia, A. rotundifolia, L. racemosa,* and *Xylocarpus*. In all viviparous and crypto-viviparous species, and non-viviparous species, *Lumnitzera* spp., and *Barringtonia racemosa*, fruits are characteristically 1-seeded irrespective of the number of ovules produced by individual flowers. In *E. agallocha* and *S. hydrophyllacea*, all ovules produced in individual flowers form seeds if fertilized. Fruits are 8–12-seeded in *X. granatum*, and 5–8-seeded in *X. mekongensis* irrespective of the number of ovules produced by flowers. In *Sonneratia* spp., the fruits are many-seeded and increase seed set rate depending

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on the number of ovules fertilized and energy resources available during fruiting phase. The propagule is a hypocotyl in viviparous and crypto-viviparous mangroves, while it is a seed in non-viviparous mangroves. All the three mangrove groups employ self-planting and stranding strategies according to the tidal conditions for the recruitment of new plants and populations across salinity gradients within the mangrove forest. Understanding the reproductive biology of mangroves is useful for effective mangrove rehabilitation programs.

Keywords Mangroves · Hermaphroditism · Monoecy · Dioecy · Mixed mating system · Pollination mechanism · Anemophily · Melittophily · Entomophily · Zoophily

3.1 Introduction

Mangrove flora represents two groups according to the habitat type within the estuarine zone, true mangroves, and mangrove associates; the former indicates the species that grow well in intertidal zones, while the latter indicates the species that grow well in both littoral and terrestrial habitats. Both groups collectively constitute highly productive components of the food web of the coastal ecosystem in general and estuarine ecosystem in particular as they are efficient in carbon sequestration. The mangrove rhizosphere zone is a home for estuarine and certain marine fauna. The root network is very important to protect nearby high lands from damage and erosion. Further, they assimilate pollutants and recycle nutrients through various biochemical processes (Upadhyay et al. 2002). In the last three decades, mangrove forest cover has been decreasing tremendously due to indiscriminate and irrational exploitation of its resources by local fishermen community and land use changes for aquaculture development and conversion to agricultural/residential/commercial activities.

Mangrove flora displays three groups according to seed and seedling characteristics, viviparous, crypto-viviparous, and non-viviparous or oviparous groups (Table 3.1). Vivipary in flowering plants is defined as the precocious and continuous growth of the offspring when still attached to the maternal parent (Goebel 1905). It is often referred to as "true vivipary" (Tomlinson 1986). There are two types of vivipary—true vivipary and crypto-vivipary. True vivipary refers to a situation where the embryo penetrates through the fruit pericarp and grows to a considerable size as a naked hypocotyl before dispersal. In this case, the developing zygote lacks, at least in part, maternal tissues that mediate its relationship with the environment. This true viviparous condition is the characteristic of all mangrove genera of Rhizophoraceae. Crypto-vivipary is a condition in which the embryo grows continuously but does not emerge out from the fruit before dispersal. This is reported in *Avicennia* (Avicenniaceae), *Aegiceras* (Myrsinaceae), *Aegialitis* (Aegialitidaceae), *Nypa* (Arecaceae), and *Pelliciera* (Pellicieraceae) (Tomlinson 1986). In both true vivipary and crypto-viviparous species, the seed lacks dormancy and the zygote is not dependent on stored nutritional support from the endosperm or carpal tissues, but

Table 3.1 Reproductive characteristics of mangrove plants

Mangrove group	Family	Plant species	Sexual system	Mating system	Pollen discharge	Pollinators	Seeds/fruit	Propagule
Viviparous	Rhizophoraceae	*Bruguiera gymnorrhiza*	Hermaphroditic	Mixed mating	Explosive	Birds, bees, butterflies	1-seeded	Hypocotyl
		Bruguiera cylindrical	Hermaphroditic	Mixed mating	Explosive	Bees, wasps, butterflies	1-seeded	Hypocotyl
		Ceriops decandra	Hermaphroditic	Mixed mating	Non-explosive	Bees, wasps, flies	1-seeded	Hypocotyl
		Ceriops tagal	Hermaphroditic	Mixed mating	Explosive	Bees, butterflies, moths, flies, wind	1-seeded	Hypocotyl
		Kandelia candel	Hermaphroditic	Mixed mating	Non-explosive	Beetles, thrips, bees, butterflies	1-seeded	Hypocotyl
		Rhizophora apiculata	Hermaphroditic	Mixed mating	Non-explosive	Wind, thrips, bees, moths	1-seeded	Hypocotyl
		Rhizophora mucronata	Hermaphroditic	Mixed mating	Non-explosive	Wind, thrips, bees, moths	1-seeded	Hypocotyl
Crypto-viviparous	Avicenniaceae	*Avicennia alba*	Hermaphroditic	Mixed mating	Non-explosive	Beetles, bugs, bees, bee-flies, wasps, ants, flies, butterflies, moths	1-seeded	Hypocotyl
		Avicennia officinalis	Hermaphroditic	Mixed mating	Non-explosive	Beetles, bugs, bees, bee-flies, wasps, ants, flies, butterflies, moths	1-seeded	Hypocotyl
		Avicennia marina	Hermaphroditic	Mixed mating	Non-explosive	Beetles, bugs, bees, bee-flies, wasps, ants, flies, butterflies, moths	1-seeded	Hypocotyl
	Myrsinaceae	*Aegiceras corniculatum*	Hermaphroditic	Mixed mating	Non-explosive	Bees, wasps, flies, butterflies, birds, wind	1-seeded	Hypocotyl
	Aegialitidaceae	*Aegialitis rotundifolia*	Hermaphroditic	Mixed mating	Non-explosive	Bees	1-seeded	Hypocotyl

(continued)

Table 3.1 (continued)

Mangrove group	Family	Plant species	Sexual system	Mating system	Pollen discharge	Pollinators	Seeds/ fruit	Propagule
Non-viviparous	Combretaceae	*Lumnitzera littorea*	Hermaphroditic	Mixed mating	Non-explosive	Birds, bees, wasps	1-seeded	Seed
		Lumnitzera racemosa	Hermaphroditic	Mixed mating	Non-explosive	Wasps, bees, butterflies, moths	1-seeded	Seed
	Euphorbiaceae	*Excoecaria agallocha*	Dioecious	Out-crossing	Non-explosive	Wind, bees, flies, butterflies	3-seeded	Seed
	Lecythidaceae	*Barringtonia racemosa*	Hermaphroditic	Mixed mating	Non-explosive	Moths, bats		Seed
	Meliaceae	*Xylocarpus granatum*	Monoecious	Out-crossing	Non-explosive	Bees, moths	8–12 seeded	Seed
		Xylocarpus mekongensis	Monoecious	Out-crossing	Non-explosive	Bees, moths	5–8 seeded	Seed
	Rubiaceae	*Scyphiphora hydrophyllacea*	Hermaphroditic	Mixed mating	Non-explosive	Bees, wind	4-seeded	Seed
	Sonneratiaceae	*Sonneratia caseolaris*	Hermaphroditic	Mixed mating	Non-explosive	Mammals, birds, bees, wasps, flies, butterflies	Many-seeded	Seed
		Sonneratia alba	Hermaphroditic	Mixed mating	Non-explosive	Wind	Many-seeded	Seed
		Sonneratia apetala	Hermaphroditic	Mixed mating	Non-explosive	Wind	Many-seeded	Seed

instead may be nourished directly from the maternal plant. The unit of dispersal is the hypocotyl, which is a "young seedling." These peculiar seedling characteristics present in mangrove plants could be adaptive features to overcome the harsh tidal environment for seedling establishment. In non-viviparous or oviparous plants, seed dormancy and seed dispersal are highly evolved and adaptive traits. The seed usually contains a reserve of food, providing the embryo with a temporary continuation of maternal support and persists through recurrent unfavorable seasons and has a perennating role; the seed is usually the stage of the life cycle at which dispersal and the colonization of new areas occur (Elmqvist and Cox 1996). Non-viviparous species are mostly mangrove associates, which grow usually in landward or low-salinity habitats.

True mangrove plants are the major constituents of the mangrove ecosystem. Some plants form conspicuous elements of the vegetation, while some others rarely form pure communities due to their inability to cope with the characteristic harsh environment that prevails in mangrove forests. Some other plants occur as mangrove associates, but they do not occur exclusively in the proximity of mangroves and may occur in transitional vegetation, landwards, and seawards; however, they do interact with true mangroves (Tomlinson 1986; Field 1995; Das 2002). The ability or inability to form populations by each plant species is determined by the inherent features of their breeding systems and by their extrinsic interactions with pollen vectors, upon which they rely for pollen dispersal and pollen receipt. These interactions can be particularly complex in animal-pollinated species because pollinator behavior can be influenced by floral morphology, plant density, floral display, and other biotic and abiotic factors (Kunin 1993; Routley et al. 1999; Franceschinelli and Bawa 2000; Mitchell et al. 2004). In mangrove plants, flowers are adapted to generalized types of pollinators in order to reduce competition for the limited available pollinators (Tomlinson 1986). Furthermore, some mangrove plants exhibit extended flowering periods as a strategy or adaptation to the foraging behavior displayed by the pollinators (Janzen 1971). Flowers occur throughout the year at least on a few mangrove plants, allowing pollinators to perform foraging activities on a regular basis (Fernandes 1999). The capacity of mangroves to convert floral visitation to flower fertilization and fruit set is an important step in the recruitment process and ultimately to the maintenance of existing mangrove communities (Coupland et al. 2006). Mangrove plants in mature communities display characteristics of pioneer species such as possessing self-compatibility and utilizing a wide variety of pollinators. The characteristic wide distribution and long-range seed dispersal of mangrove plants may also favor a broad range of pollen vectors (Azuma et al. 2002). Few studies have assessed how successful mangroves are at utilizing pollinators, how much reproductive effort is required to produce a single propagule, and whether propagule production is limited by resources or by pollinators. A more complete understanding of the reproductive biology of mangroves is useful, particularly due to the growing pressures on mangrove environments, and for effective mangrove rehabilitation programs (Coupland et al. 2006). Finally, the reproductive success, structure, and function of individual mangrove plant species are subject to a combination of geophysical, geographical, geological, hydrographical, bio-geographical, climatic, edaphic, and environmental factors (Bandaranayake 1998).

In this chapter, the information on the reproductive ecology of important viviparous, crypto-viviparous, and non-viviparous mangrove plant species has been briefly reviewed. In this review, the sexual system, pollination mechanism/syndrome, pollinators, and seedling or seed dispersal aspects have been examined (Table 3.1) to understand their role in the reproductive success and perpetuation of respective species in mangrove forest ecosystems.

3.2 Viviparous Species

3.2.1 Family Rhizophoraceae

It is a small pan-tropical family of tropical or subtropical flowering plants. It is often referred to as the "true mangrove" family. It comprises 120 species of trees and shrubs distributed in 16 genera; most are native to the Old World (Watson and Dallwitz 1992), but only four genera with about 18 species inhabit mangroves (Duke et al. 1998; Ghosh et al. 2008). The mangrove genera include only *Bruguiera, Ceriops, Kandelia,* and *Rhizophora* (Tomlinson et al. 1979). All species in these genera have the same basic floral structure, but have different pollination mechanisms (Ghosh et al. 2008). The floral parts are uniformly protected within comparatively thick and fleshy calyx lobes; a number of filiform appendages are present at the apex of the petals, and the number of stamens is usually twice as many as the number of petals, but in *Kandelia*, the stamens are numerous (Das et al. 1994). Variation in these features such as size and orientation of flowers, number of flowers per inflorescence, number of stamens, time of stamen dehiscence, and method of pollen discharge has been shown to have direct relevance to pollination biology (Ghosh et al. 2008). A brief review of the available information on pollination ecology of all four genera is provided here.

3.2.1.1 Genus *Bruguiera*

The genus *Bruguiera* comprises six hermaphroditic species, namely *B. cylindrica, B. gymnorrhiza, B. parviflora, B. sexangula, B. aristata,* and *B. hainesii*; all belong to the Indo-Malayan group of mangroves that extend from East Africa to Australia and the West Pacific. The *Bruguiera* genus is segregated into two groups of species based on flower size and inflorescence type: Large, solitary-flowered group includes *B. gymnorrhiza, B. sexangula,* and *B. exaristata,* while small, many-flowered group includes *B. parviflora, B. cylindrica,* and *B. hainesii*. In all six species, the anthers dehisce in the flower bud, the stamens are enclosed in pairs under tension within the petals, and the pollen is released explosively when the flower is triggered (Tomlinson 1986). Two main agents trigger the process, birds in the large-flowered species and butterflies in the small-flowered species (Tomlinson et al. 1979; Juncosa and Tomlinson 1987; Chiou-Rong et al. 2005). Untriggered petals may retain their tension for up to 10 days, and they may be lost without ever opening. In large-flowered species, the out-breeding mechanism is weak, and it occurs via partial protandry. It is not known whether a similar trend exists in the small-flowered species (Tomlinson et al. 1979; Tomlinson 1986). Details of pollination ecology are only available *B. gymnorrhiza* and *B. cylindrica*.

3.2.1.1.1 *B. gymnorrhiza* and *B. cylindrica*

B. gymnorrhiza and *B. cylindrica* are polyhaline, evergreen tree species (Solomon Raju 2013). *B. gymnorrhiza* is a year-long bloomer with profuse flowering during April–June, while *B. cylindrica* blooms during specific period from September to March. Solomon Raju (2013) reported that *B. cylindrica* produces 3-flowered cymes not the many-flowered cymes as stated by Tomlinson (1986). *B. gymnorrhiza* flowers are pendulous, while *B. cylindrica* flowers are horizontal or downward or slightly erect and placed outward in the crown of leaves (Solomon Raju 2013). The two species show the same daily anthesis schedule, which is confined to before noon period. In *B. gymnorrhiza*, the flowers are white with pinkish to reddish-white calyx, while in *B. cylindrica*, they are creamy-white with light green calyx. In both, the flowers have concealed nectar, elaborate complex petal-stamen configuration, and presence of basal clumps of hairs and marginal hairs, which suggest a specialized explosive floral mechanism functional only when pollinating agents are involved. In *B. gymnorrhiza,* there are 14 petals each enclosing 2 stamens; this petal–stamen configuration requires multiple visits of pollinators for the explosion of all petals. In *B. cylindrica*, the flowers have only 7 or 8 petals with 14 or 16 stamens and closely spaced; this arrangement with a reduced number of petals in relation to the small flower size is an important adaptation for the explosion of all petals of the flower and subsequent pollination in a single or two visits of the pollinator insects. Petal explosion is violent in *B. gymnorrhiza,* while it is non-violent in *B. cylindrica*.

B. gymnorrhiza flowers are recurved and typically point backwards into the crown of the tree (Solomon Raju 2013). Nectar is produced in abundance and held in the deep floral cup. The calyx is red, a color attractive to birds. Azuma et al. (2002) examined *B. gymnorrhiza* flowers for scent characteristics and reported that the floral scent is lacking and the floral characteristics are indicative of bird pollination. Ghosh et al. (2008) also reported that the flowers are adapted to a range of flower visitors such as birds for pollination. Ge et al. (2003) mentioned that the flowers are pollinated by birds or butterflies. Solomon Raju (1990) reported that the flowers were exclusively pollinated by three species of passerine birds, *Nectarinia asiatica, N. zeylonica,* and *Zosterops palpebrosus* at the Coringa Mangrove forest, India, when the site was ecologically healthy, and there was little human interference. However, more recently Solomon Raju (2013) reported that the Coringa mangrove forest was ecologically degraded and fragmented due to land use changes, and as a consequence, birds have never been observed visiting the flowers of *Bruguiera* or any other mangrove plant species. Under changed land cover in this mangrove forest, *B. gymnorrhiza* is exclusively pollinated by bees consisting of *Apis, Nomia,* and *Halictus* genera. These bees trip the tensed petals to release the stamens, which in turn eject a cloud of pollen from the already dehiscent anthers. During this process, the bees get a pollen shower all over their body, especially on their dorsal side. *B. gymnorrhiza* has become melittophilous; the bees are reliable pollinators when compared to bird pollinators. The ability of the plant to utilize birds and bees is certainly an adaptive trait and is also essentially required for the survival, colonization, and expansion of its geographical range (Tomlinson 1986).

Tomlinson et al. (1979) stated that the small-flowered *B. cylindrica* is pollinated by butterflies and small insects. In this species, the small flowers with a flat calyx cup containing a small quantity of nectar, greenish-yellow petals are oriented nearly in erect state and display their presence to the outside of the tree crown. Thin branchlets are insufficient for bird perching. Pollen release occurs by a delicate, distal stimulation of petals. All these floral characters have been listed as adaptations for butterfly pollination. Solomon Raju (2013) reported that *B. cylindrica* is pollinated by *Nomia* bees and *Odynerus* and *Polistis* wasp species only. Tomlinson (1986) mentioned that bees and wasps represent a group of pollinators that nest in mangroves, and some populations are completely dependent on mangal for their existence. Ghosh et al. (2008) reported that some wasps and flies are highly dependent on mangroves for nesting. In the light of these reports, bees and wasps are reliable pollinators since they nest in mangroves and collect forage from the same plants for their nutrition (Solomon Raju 2013).

Tomlinson (1986) mentioned that pollination may favor outcrossing in *B. gymnorrhiza*. Kondo et al. (1987) reported that *B. gymnorrhiza* is both autogamous and allogamous. Ge et al. (2003) stated that this species has a mixed mating system with outcrossing as a main system. Solomon Raju (2013) also reported that *B. gymnorrhiza* is both autogamous and allogamous, but all modes are functional only when petal explosion is manipulated; this suggests that pollination is essentially vector-dependent and fruit set is completely a consequence of the foraging activity of bee pollinators. This author mentioned that the fallen flowers presenting some or a few unexploded petals are an indication of the absence of anemophily. Similar vector-dependent mixed mating system is functional in *B. cylindrica*. Such a mating system facilitates fruit set in the presence of pollinators even in isolated trees of both the species of *Bruguiera.*

Solomon Raju (2013) reported that *B. gymnorrhiza* flowers are 6-ovuled and *B. cylindrica* flowers are 4-ovuled, but only one ovule develops into mature seed in both the species. The persistent and expanded calyx gives protection to the fruit; the mature fruit is well seated within the calyx. Seeds germinate to produce cylindrical chlorophyllous naked hypocotyls, while they are still attached to the parent plant. The chlorophyll content enables the hypocotyls to carry out photosynthesis, while the parent plant supplies the water and necessary nutrients (Tomlinson 1986; Selvam and Karunagaran 2004). Solomon Raju (2013) reported that the hypocotyls of both *Bruguiera* species hang downward and detach from the residual fruit, leaving behind their cotyledons. The hypocotyls float and disperse using tidal water. Both species use self-planting and stranding strategies according to the tidal conditions.

3.2.1.2 Genus *Ceriops*

The genus *Ceriops* comprises three species, *C. australis, C. decandra,* and *C. tagal. C. australis* has a limited distribution area and endemic to the littoral zone of Australasia, which represents Australia, New Zealand, and New Guinea. *Ceriops decandra* is widely distributed from East Africa and Madagascar throughout tropical Asia and Queensland to Melanesia and Micronesia. *Ceriops tagal* typically grows in inner mangroves and is geographically widespread from East Africa through India and Malaysia to South China. All the three species are hermaphroditic and show a distinct trend for self-incompatibility (Tomlinson 1986). There is some debate on the species status of *C. australis* due to its close resemblances with *C. decandra*. Information on pollination ecology of *C. decandra* and *C. tagal* has been briefly reviewed.

3.2.1.2.1 *C. decandra*

Solomon Raju and Henry (2008) reported that *C. decandra* is a common polyhaline, evergreen, and year-long blooming tree species. The flowering is very intense during October–November, while it is sparse during the remaining period of the year. The floral characteristics such as small white flowers lacking fragrance, simple stamen–petal configuration, short, thick filaments, and production of a small volume of nectar suggest a simple floral mechanism. Juncosa and Tomlinson (1987) explained the stamen–petal configuration in *C. decandra*. These authors mentioned that the basal petal edges equipped with a small patch of short hairs have no evident function in the functioning of floral mechanism. These authors also reported that petal clavate appendages have abundant xylem elements with a significant reservoir of water and hydathodes at or near the termini; they have significance in flower function under extreme water pressure deficits during the day in mangrove swamps. The presence of abundant xylem elements and hydathodes and their function in petal appendages have been considered as adaptations for pollination during the day. Therefore, the floral mechanism is unspecialized and reflects an ancestral state when compared to the elaborate and specialized floral mechanism functional in *Ceriops tagal*. Tomlinson (1986) reported that *C. decandra* is entomophilous and wasps and flies are suitable for pollination. Juncosa and Tomlinson (1987) noted that *Trigona* bees and other insects visit the flowers of *C. decandra*. Ghosh et al. (2008) reported that wasps and flies act as pollinators of *C. decandra*. Solomon Raju and Henry (2008) reported that bees and wasps are the pollinators of *C. decandra*.

Tomlinson (1986) mentioned that *C. decandra* is self-compatible and its pollination may favor out-crossing. Coupland et al. (2006) reported that autogamy is lacking and hence fruit set rate is very low in this species. Solomon Raju and

Henry (2008) reported that *C. decandra* with strong protandry is self-pollinating and cross-pollinating. These authors reported that natural fruit set is limited to the lowest level despite consistent pollinator activity. In fruited flowers, ovule abortion is the rule and always only one ovule produces seed. Production of two seeds and hence two hypocotyls per fruit is a rare occurrence. The ovule abortion seems to be an effective option for the plant to save resources and use them to produce one-seeded, viable fruits. Despite this effort by the plant, it produces a few yellow-colored, achlorophyllous, and inviable hypocotyls, which might be an indication of constraints in the availability of resources to the maternal parent.

Solomon Raju and Henry (2008) reported that in *C. decandra*, the single seed formed in the fruit is not dormant and germinates immediately producing a spindle-shaped naked upright chlorophyllous hypocotyl or seedling, while still attached to the maternal parent. A yellow collar structure emerges between the fruit and hypocotyl about 2 weeks prior to detachment of the latter. Viviparous reproduction allows hypocotyls to develop some salinity tolerance before being released from the parent tree. The hypocotyl characteristics help to develop buoyancy for dispersal and structural stability for protection against damage. Therefore, the characteristics such as mixed breeding system, simple floral mechanism, generalist pollinators, true vivipary, planting and stranding strategies for establishment, and absence of crab predation on seedlings account for the successful colonization and common occurrence of *C. decandra*.

3.2.1.2.2 *C. tagal*

C. tagal is a seaward evergreen and winter-blooming species. The floral characteristics such as white petals, strong fragrance, complex petal–stamen configuration, and production of nectar suggest an elaborate and specialized floral mechanism. The petals require an external delicate touch for the explosive release of stamens. The helically coiled hairs at the lower margins of the petals help to propagate explosive pollen release effectively (Juncosa and Tomlinson 1987; Solomon Raju and Henry 2008). The petal clavate appendages lack hydathodes and abundant xylem, but these structures are present and play a role in flower function under extreme water pressure deficits during the day in *C. decandra* (Juncosa and Tomlinson 1987). The absence of hydathodes and abundant xylem in petal appendages may make them very light and provide necessary triggers for petal explosion by a delicate touch of a gentle wind force or forager. Suitably triggered, the petal margins unzip instantaneously and fly apart, releasing the stamens, which catapult the loose pollen toward the center of the flower, often as a visible cloud. Each petal encloses a pair of stamens and behaves independently so that multiple visits are possible. Then, individual flowers present combinations of closed and open petals as in *Bruguiera* species (Tomlinson 1986). Un-triggered petals retain their tension for up to 7 days and fall off without ever opening. Similar explosive pollination mechanisms have been reported in *Bruguiera* species for which the flower tripping agents are birds and butterflies (Tomlinson et al. 1979; Ge et al. 2003).

Solomon Raju and Henry (2008) reported that *C. tagal* flower buds open in the evening, emitting a faint but fragrant odor, and remain in place for about a week. Tomlinson (1986) reported that night-flying insects such as nectar-feeding moths are probable pollinators and bees may be daytime visitors of *C. tagal*. Solomon Raju and Henry (2008) reported that *C. tagal* flowers are not foraged by night-flying insects but only during the daytime, by honeybees, flies, and butterflies. Bees and flies trip the petals, which results in pollination, while butterflies have no role in tripping the petals to result in pollination, but the butterflies may affect pollination in tripped flowers. The petals show color change to red from top to bottom gradually to make flowers either inconspicuous or unattractive, either at a distance or at a close range in order to make pollinators visit rewarding white flowers to affect pollination (Gori 1983). Wind is also effective in tripping the petals, but it contributes to self-pollination only (Solomon Raju and Henry 2008).

Solomon Raju and Henry (2008) stated that *C. tagal* flowers are strongly protandrous, self-compatible, but the long flower life and long period of stigma receptivity and high pollen-ovule ratio indicate that the plant is mainly outcrossing. Huang et al. (2008) also predicted that *C. tagal* flowers with self-compatibility may favor outcrossing. Solomon Raju and Henry (2008) reported that natural fruit set in *C. tagal* is limited despite sufficient pollination effected by insects and wind. Fruits are typically single-seeded although six ovules are produced per flower; this situation is attributed to scarcity of resources and other factors prevailing at the locations of *C. tagal*. Seeds germinate to produce naked chlorophyllous hypocotyls, which grow downward, while the fruit is still attached to parent plant. The hypocotyls are almost double the length of *C. decandra.* This is an important field characteristic feature to distinguish it from *C. decandra* in which the hypocotyls grow upward. Tomlinson (1986) stated that the downwardly hanging hypocotyl is also a characteristic of *Bruguiera, Rhizophora,* and *Kandelia*. Das and Ghose (2003) noted that the cotyledons of *C. tagal* fuse entirely forming a cylindrical collar, which distinguishes the fruit from the hypocotyl. Aksornkoae et al. (1992) reported that the cylindrical collar of *C. tagal* hypocotyl is also a characteristic of the hypocotyl of *Rhizophora*, which is reddish-brown and of the hypocotyl of *Kandelia,* which is yellow and the hypocotyl is about double the length of *C. tagal*.

Clarke et al. (2001) reported that *C. tagal* with epigeal seed germination and elongated and pointed hypocotyls with straight curvature fall freely from the mother plant and plant themselves into the mud at the same site during low tide period, but if the hypocotyls fall during high tides, they float to another site for settlement. However, Solomon Raju and Henry (2008) reported that *C. tagal* hypocotyls only fall down and settle at parental sites. McGuinness (1997) reported that hypocotyls of *C. tagal* in northern Australia dispersed very short distances with only 9% moving more than 3 m from the parent tree. Moreover, a high percentage of them were either damaged or eaten by animals.

3.2.1.3 Genus *Kandelia*

Kandelia is a monotypic genus, ranging from the Ganges Delta, Burma, through Southeast Asia to south China, the Ryukyu Islands, and south Japan. It occupies a narrow niche in the mangrove forest and typically occurs in the back-mangrove communities or on the banks of tidal rivers farther inland. A single understory tree hermaphrodite species, *K. candel,* has been assigned to this genus. Its floral biology resembles *C. decandra* (Tomlinson 1986). Juncosa and Tomlinson (1987) documented that *K. candel,* petals, stamens, and style are comparatively long and slender and the flowers open in the early morning. They suggested that moths are the most likely flower visitors of this species. Murai et al. (2000) reported that *K. candel* produces a floral scent with two nitrogen-containing compounds indole and methyl anthranilate. The last is an attractant for *Thrips hawaiiensis* and *T. coloratus*. Imai et al. (1997) mentioned that the floral scent chemical methyl anthranilate in *K. candel* also attracts the beetle *Anomala rufocuprea*. Pellmyr (1986) reported that butterflies are also attracted to the floral scent chemical methyl anthranilate. Mason et al. (1989) and Azuma et al. (2002) reported that methyl anthranilate from the floral scent of *K. candel* repels some birds. Sun et al. (1998) reported that *K. candel* is a seaward species, which is a major "pioneer" species responsible for seaward extension of mangrove communities. It appears to have a non-specialized pollination mechanism, which is pollinator-dependent for fruit set, involving generalist pollinators such as bees and butterflies. This species is frequently foraged by *Apis mellifera, Xylocopa iridipennis* and butterflies, *Delias pasithoe, Euchrysops cnejus* and *Euploea midamus* and *Heliophorus epicles* in Hong Kong mangrove forest. These authors expressed that it is not known whether these insect visitors actually affect pollination; however, bee activities may lead to substantial geitonogamous selfing. Ge et al. (2003) reported that *K. candel* is primarily out-crossing as its flowers display entomophilous characters.

Chiou-Rong et al. (2003) reported a new species of *Kandelia, K. obovata,* based on the populations located on the north of the South China Sea. This species is cold-tolerant and survives and reproduces well. These authors documented certain characters that differentiate *K. obovata* from *K. candel*. But, the information on the reproductive ecology of *K. obovata* is not available.

3.2.1.4 Genus *Rhizophora*

The genus *Rhizophora* is pan-tropical and distributed in climatically rather uniform coastal environments, but with limited extension into the subtropics. It has eight evergreen tree species of which three species are putative hybrids. Based on their distribution range, they are categorized into Eastern and Western species. Eastern species are *R. apiculata, R. mucronata, R. stylosa, R. samoensis, Rhizophora* x *lamarckii,* and *Rhizophora x selala,* while western species are *R. mangle, Rhizophora x harrisonii, and R. racemosa*. *R. apiculata* is a common and dominant constituent of mangroves in the Malesian region as far west as Queensland and Papua but restricted to the east (north) coast of this island. *R. mucronata* ranges from East Africa to the Western Pacific and in much of the Indian Ocean areas; it is the sole representative of the genus. All species are hermaphroditic, weakly protandrous, and likely self-compatible (Tomlinson 1986). Most species are considered to be wind-pollinated because of their high pollen/ovule ratios, floral phenology, and morphology (Tomlinson et al. 1979; Tomlinson 1986). The stigmas are not elaborated for wind pollination. Anemophily has its origin to an unspecialized early floral developmental pattern (Juncosa and Tomlinson 1987). The flowers are visited by bees, thrips, and other insects (Tomlinson et al. 1979; Tomlinson 1986; Kondo et al. 1987). Adaptations for anemophily include the occurrence of flower-opening at any time of day, the wide or slight opening of calyx lobes, and the dehiscence multi-locellate anthers in flower bud via the fall of adaxial flap against the base of the style and the dry, light pollen. Dispersal of pollen is easily facilitated when the flower is shaken by the wind and is further promoted by hygroscopic movement of the intertwined petal hairs, which are released in a flicking motion. This pollen dispersal mechanism occurs in all species. The calyx lobes diverge least and the petals neither recurve nor retain pollen because they are glabrous and a simple pepper pot mechanism is sufficient to disperse the pollen dust. Slow development of the flowers such that they are mature only below the leafy rosette on each branch constitutes a simple device, which facilitates pollen dispersal by minimizing interference of the tree's own foliage. Equally, this may facilitate capture of pollen by receptive flowers. Extensive pure stands of trees occurring in a windy environment assure the success of wind pollination (Tomlinson et al. 1979). Bees collect mainly pollen from *Rhizophora* species and in the process affect pollination (Tomlinson 1986). Thrips are common in *Rhizophora* flowers (Tomlinson 1986). The transformation of pollination mechanism from an original animal-pollinated ancestral condition to a wind-pollinated condition might have evolved to escape the competition for animal pollination that otherwise predominates in mangrove communities (Tomlinson et al. 1979; Juncosa and Tomlinson 1987).

The pollination biology of individual species is poorly studied. Kress (1974) reported that the floral odor and production of nectar in *R. mangle* and *R. stylosa* are considered to be vestigial entomophilous characteristics, which might have had an ancestral entomophilous condition and gradually evolved for anemophily. Tomlinson (1986) reported that *R. stylosa* flowers are generally incapable of self-pollination. Azuma et al. (2002) worked out the chemical profile of floral scent of *R. stylosa* and reported that it is composed of several phenylpropanoids in addition to other classes of volatiles. The scent profile and all other floral characteristics are indicative of animal pollination in *R. stylosa*. A brief review of pollination biology of *R. apiculata* and *R. mucronata* is provided here.

3.2.1.4.1 *R. apiculata* and *R. mucronata*

R. apiculata and *R. mucronata* are polyhaline, evergreen true viviparous tree species (Solomon Raju 2013). *R. apiculata* blooms throughout the year but shows profuse flowering for 2 months during August–September, while *R. mucronata* flowers for about 6 months with profuse flowering during August–September. The year-long flowering in *R. apiculata* and extended flowering in *R. mucronata* allows the plant to set fruit continuously, and this characteristic may be a fail-safe strategy against pollination limitation and propagule predation.

R. apiculata flowers are sessile and borne in pairs below the leafy cluster, while *R. mucronata* flowers are pedicellate and borne in 4-flowered cymes within leaf clusters (Solomon Raju 2013). The flowers of *R. mucronata* are also quite prominent and attractive to flower foragers when compared to those of *R. apiculata*. In both, the floral characters exhibit certain adaptations for anemophily. The flowers are pendulous, point downward at maturity, and situated below or within the leafy crown; this floral orientation is important to minimize interference of foliage for effective pollen dispersal by wind. The sepals diverge least, while the petals are glabrous and do not recurve or retain pollen grains in *R. apiculata*. Tomlinson (1986) reported that in *R. mucronata* the petals equipped with marginal hairs promote anemophily by their hygroscopic movements. Solomon Raju (2013) reported that in *R. apiculata* and *R. mucronata*, late morning anthesis, high pollen/ovule ratio, light powdery pollen, absence of an attractive color and odor, and absence of abundant pollinators are some important characteristics for anemophily. In both, the late morning anthesis is another important characteristic for the effective dispersal of dry powdery pollen grains from the already dehiscent anthers in mature buds due to moderate levels of temperature and humidity present at that time. The two species occur as pure stands mostly and are located in a windy environment along the creeks. This form of distribution may facilitate effective dispersal of pollen between individual trees and receptive sites of flowers receive wind-borne pollen. Kondo et al. (1987) reported that the pollen grains have evolved characteristics for anemophily. Tomlinson et al. (1979) also experimentally proved that wind-borne pollen is abundant, and hence, anemophily is most efficient in pure stands of *Rhizophora* species. Solomon Raju (2013) reported that *R. apiculata* and *R. mucronata* despite having several adaptations for anemophily, their stigma is not elaborated in the manner usual for wind-pollinated species to capture wind-borne pollen. The absence of marginal hairs on petals, lack of elaboration of stigma, absence of odor, and presence of traces or minute quantity of nectar seem to be vestigial characteristics of entomophily. Kondo et al. (1987) reported that *R. mucronata* is anemophilous but is also pollinated by small insects like *Camponotus* sp., *Onychostylus pallidiolus,* and a *Collembola*. Solomon Raju (2013) reported that *R. apiculata* and *R. mucronata* offer only pollen as reward to foragers, and they are pollinated by bees of *Nomia, Trigona,* and *Halictus; R. mucronata* is also pollinated by *Ceratina, Xylocopa,* and moths. Thrips of the suborder Terebrantia use these two *Rhizophora* species as their breeding and feeding sites; the feeding activity contributes to self-pollination, but it also contributes to cross-pollination in plants growing as pure stands. This author stated that entomophily is the original pollination mechanism, but it is now evolved to transitional anemophily in both *R. apiculata* and *R. mucronata*. Such a transitional pollination mechanism facilitates these species to utilize both wind and insects as pollinating agents for the success of sexual reproduction. In this context, Solomon Raju (2013) noted that anemophily in *R. apiculata* and *R. mucronata* enables them to escape from the competition for insect pollinators and also to set fruit in the total absence of insect pollinators, which facilitates them to become established as isolated individuals in new environments far from parental sites.

In *R. apiculata* and *R. mucronata*, the flowers are 4-ovuled, but only one ovule develops into mature seed, which germinates immediately to produce a naked cylindrical hypocotyl or seedling, while still on the maternal parent (Solomon Raju 2013). Selvam and Karunagaran (2004) reported that the seedlings of *R. apiculata* and *R. mucronata* develop chlorophyll and actively photosynthesize; the parent tree supplies the water and necessary nutrients. The seedlings of *R. apiculata* and *R. mucronata* hang downwards and detach from the residual fruit at the collar end, leaving behind its cotyledons, and falls off the maternal parent (Solomon Raju 2013). Christensen and Wium-Andersen (1977) speculated that in *R. apiculata*, the development from visible flower buds to mature propagules lasts about 2 years, while Muniyandi (1986) reported that the propagule of *R. apiculata* takes 8 months to grow to full length after fertilization. Muniyandi (1986) reported that the seedlings of *R. mucronata* take 16 months to grow to full length after fertilization in *R. mucronata*. But, Solomon Raju (2013) reported that *R. apiculata* and *R. mucronata* produce mature seedlings from flower buds in a time span of about 4 months only, but it may vary depending on the location.

3.3 Crypto-Viviparous Species

3.3.1 Genus **Avicennia** *(Avicenniaceae)*

The family Avicenniaceae comprises only one genus *Avicennia* with at least 8 tree species (*Avicennia balanophora* Stapf & Moldenke., *Avicennia bicolor* Standl., *Avicennia germinans* (L.) L., *Avicennia integra* N.C. Duke., *Avicennia marina* (Forssk.) Vierh., *Avicennia officinalis* L., *Avicennia schaueriana* Stapf & Leechm. ex Moldenke, and *Avicennia tonduzii* Moldenke), which grow in the inter-tidal zone of coastal mangrove forests and range widely throughout tropical and warm temperate regions of the world (Tomlinson 1986; Duke 1991). These species occupy diverse mangrove habitats, either within the normal tidal range or in the back mangal so have a high tolerance of hyper-saline conditions. Three species, *A. germinans, A. schaueriana,* and *A. bicolor,* occur in Atlantic-East Pacific and five species, *A. marina, A. alba, A. officinalis, A. integra,* and *A. rumphiana,* in the Indo-West Pacific (Duke 1992). The East Africa and Indo-Pacific species include *A. officinalis, A. marina, A. alba, A. lanata, A. eucalypti folia,* and *A. balanophora,* but only the first three species reached the Indian subcontinent (Duke et al. 1998). *A. officinalis* has a wide range from South India through Indo-Malaya to New Guinea and eastern Australia. *A. marina* has the broadest distribution, both latitudinally and longitudinally with a range from East Africa and the Red Sea along tropical and subtropical coasts of the Indian Ocean to the South China Sea, throughout much of Australia into Polynesia and as far as Fiji, and south to the North Island of New Zealand (Tomlinson 1986). *A. marina* has the distinction of being the most widely distributed of all mangrove tree species. The ubiquitous presence in mangrove habitats around the world is due to its ability to grow and reproduce across a broad range of climatic, saline, and tidal conditions and to produce large numbers of buoyant propagules annually (Duke et al. 1998). *A. alba* has a wide distribution from India to Indochina, through the Malay Archipelago to the Philippines, New Guinea, New Britain, and northern Australia.

3.3.1.1 *Avicennia alba, A. marina* and *A. officinalis*

A. alba, A. marina, and *A. officinalis* have very similar flowers, and Tomlinson (1986) suggested they would have the same class if not by the same species of pollinators. *Avicennia officinalis* is self-compatible and occasionally self-pollinating. Self-pollination of individuals is unlikely due to protandry, but the sequence and synchrony of flowering together with pollinator behavior favor geitonogamy. Clarke and Meyerscough (1991) reported that *A. officinalis* is pollinated by a variety of insects in Australia, and *A. marina* is visited by ants, wasps, bugs, flies, bee flies, cantherid beetles, and moths, but the most common visitor is *Apis mellifera*. Solomon Raju et al. (2012) reported that A. *alba, A. marina,* and *A. officinalis* are hermaphroditic and have similar floral architecture, and the flowers are of open type and shallow with small aliquots of nectar, which is exposed to rapid evaporation, which results in increased nectar sugar concentration, so all three species are pollinated by bees, wasps, flies, and butterflies. Despite being pollinated by different classes of insect pollinators and having the ability to self-pollinate even in the absence of insect activity, the natural fruit set stands at 42–58% only. Wium Andersen and Christensen (1978) reported that *A. marina* flowers during April–May. Mulik and Bhosale (1989) noted that *A. marina* flowers from April to September, while *A. officinalis* flowers from March to July. Solomon Raju et al. (2012) reported that *Avicennia alba, A. marina,* and *A. officinalis* are polyhaline evergreen tree species and flower simultaneously during June–August in Coringa mangrove Forest, Andhra Pradesh, India. In all, the flowers are strongly protandrous and the stamens with dehisced anthers over-arch the stigma. The stigma shows post-anthesis growth. It is erect and seated in the center of the flower in *A. alba* and *A. marina,* while it is bent and situated below the adaxial corolla lobe in *A. officinalis*. The erect stigma does not change its orientation throughout the flower life in *A. alba* and *A. marina,* while the bent stigma becomes erect on the third day. The stigma is bifid and appressed on the day of anthesis in all the three species; it remains in the same state also on day 2 in *A. officinalis*. The stigma commences receptivity by diverging in dorsiventral plane; it is receptive on days 2 and 3 in

A. alba and *A. marina* and on days 3, 4, and 5 in *A. officinalis*. In all the three species, self-pollination of individual flowers is unlikely on the day of anthesis due to protandry, but the stamens with dehisced anthers over-arching the stigma may facilitate autogamy during flower life. They are self-compatible, and fruit set occurs through autogamy, geitonogamy, and allogamy. Clarke and Meyerscough (1991) also reported that *A. marina* is protandrous, self-compatible, and self-pollinating, but the fruits resulting from spontaneous self-pollination showed a higher rate of maternal abortion reflecting an inbreeding depression. Coupland et al. (2006) reported that in *A. marina*, autogamy is most unlikely and emphasized the importance of pollen vectors to the reproductive success. Solomon Raju et al. (2012) reported that autogamy is functional in *A. marina*. Clarke and Meyerscough (1991) reported from Australia that in *A. marina*, some trees flower, and fruit every year, while others do not flower every year. Solomon Raju et al. (2012) documented that in India *A. alba, A. marina,* and *A. officinalis* flower annually and also the flowering is uniform on all branches within a tree.

The flowers of *A. alba, A. marina,* and *A. officinalis* are 4-ovuled, but only one ovule develops into mature seed in each fruit (Solomon Raju et al. 2012). Seeds are not dormant and germinate immediately to produce chlorophyllous seedling, which remains within the fruit, while still on the maternal parent. The seedling actively photosynthesizes, while the maternal parent supplies the water and necessary nutrients (Selvam and Karunagaran 2004). In *Avicennia* species, the propagules are small and light, and the entire embryo is buoyant after detachment from the maternal parent. Gradually, the fruit pericarp is lost exposing the leathery succulent cotyledons to tidal water. Rabinowitz (1978) reported that *A. marina* has an absolute requirement for a stranding period in order to establish since its propagules always float in tidal water. Solomon Raju et al. (2012) reported that *Avicennia* species exhibit self-planting strategy at low tide and stranding strategy at high tide. However, their seedlings disperse widely in tidal water, but establishment is mainly stationed in the polyhaline zone.

Coupland et al. (2006) reported that *Avicennia* propagules are a rich source of nutrients and attract a diverse range of insect predators, which in turn influence the rate of seedling maturation. Resource constraints and insect predation on developing fruit and seedlings may both act to reduce fruit set. In *A. marina*, the seedlings tend to be high in nutritive value and have relatively few chemical defenses (Smith 1987; McKee 1995) and tend to exhibit a pattern of very rapid initial predation (Allen et al. 2003). Solomon Raju et al. (2012) reported that the rose-ringed parakeet, *Psittacula krameri,* acts as a predator on the seedlings of *A. alba* and *A. marina* only.

3.3.2 Genus Aegiceras *(Myrsinaceae)*

The genus represents two evergreen hermaphroditic tree species, namely *A. corniculatum* and *A. floridum,* which are restricted to mangrove communities in the Asian tropics, with a distribution from India and Ceylon to South China and

Hong Kong, through Malesia to the Philippines, New Guinea, and tropical Australia. *A. corniculatum* has sweet-scented flowers, while *A. floridum* has sour-smelling flowers. *A. floridum* is restricted to northern Borneo, Java, the Moluccas, and Celebes throughout the Philippines to Indochina. It is uncommon, and its floral description and reproductive biology are completely unknown (Tomlinson 1986).

Henry (2009) reported that *A. corniculatum* is a mesohaline evergreen species. It is a typical dry season bloomer, but sporadic flowering also occurs at population level through the year. The floral characteristics such as morning anthesis, scent production, zygomorphic symmetry, short-tubed corolla with sex organs exposed, pollen structural features, and nectar production suggest adaptations for pollination by any class of animals. Tomlinson (1986) reported that *A. corniculatum* is pollinated by bees. Pandit and Choudhury (2001) reported that *A. corniculatum* is pollinated by butterflies, bees, wasps and flies, and also birds in Orissa mangrove forest, India. Henry (2009) reported that bees, wasps, flies, and butterflies are the pollinators of *A. corniculatum*. Further, this author also stated that the light and dry small pollen grains and medifixed versatile anthers of *A. corniculatum* facilitate anemophily.

Pandit and Choudhury (2001) mentioned that the flowers of *A. corniculatum* would be able to self-pollinate with the simultaneous anther dehiscence and stigma receptivity and with the stigma position at the level of the anthers. Ge and Sun (1999) reported that *A. corniculatum* is self-compatible and capable of autogamy but suggested that insect pollinators are required for a higher level of fruit set. These authors observed low levels of genetic variation in this tree occurring in China; this condition is attributed to the function of self-pollination. Henry (2009) reported that *A. corniculatum* produces fruiting through autogamy, wind, and insects, but fruit set is highest only in the flowers pollinated by insects.

Ge and Sun (1999) reported that numerous flattened ovules are embedded in the rounded, somewhat fleshy, and short-stalked free central placenta in *A. corniculatum*; it may cause an underestimation of ovule number. Pandit and Choudhury (2001) reported that each fruit of *A. corniculatum* bears only a single seed. But resource availability limits fruit production as it often grows in pure stands. Henry (2009) reported that in *A. corniculatum* the ovules per ovary are 35, but only one ovule produces seed in each fruit. Seeds are not dormant and produce hypocotyls within the fruit pericarp, while still attached to the parent tree. Hypocotyls detached from parent trees float only if they are accompanied with the fruit pericarp. Self-planting and stranding strategies are effective for the dispersal and establishment of hypocotyls.

3.3.3 Genus **Aegialitis** *(Aegialitidaceae)*

The genus *Aegialitis* was previously placed in Plumbaginaceae but was later placed in Aegialitidaceae due to anomalous secondary thickening, abundant sclereids, incipiently viviparous seeds, monomorphic pollen, and homostylous flowers

(Weber-El Ghobary 1984; Tomlinson 1986). This genus represents only two shrubs or small tree species, *A. annulata* and *A. rotundifolia*. *A. annulata* is distributed in Australia and eastern Malaysia (Tomlinson 1986), while *A. rotundifolia* is distributed in South Africa and Southeast Asia (Kathiresan and Bingham 2001). *A. rotundifolia* has been reported to occur in Myanmar, Bengal, and the Andaman by Tomlinson (1986). Later, Naskar and Mandal (1999) reported this species as occurring in the Sundarbans, Andaman and Nicobar Islands, and Mahanadi delta of Orissa only. Henry (2009) reported that *A. rotundifolia* occurs in the seaward Nachugunta Reserve Forest of Krishna Mangroves in Andhra Pradesh, India. *A. rotundifolia* due its distribution in high saline areas has a mechanism to excrete the absorbed salt via salt glands present on the leaf blades (Scholander 1968) and prefers or even requires exposed high saline sites where it effectively withstands wave and tidal action (Tomlinson 1986; Aksornkoae et al. 1992; Henry 2009).

Aegialitis annulata is a dry season bloomer, but it completes flowering prior to the onset of extreme dry conditions in the month of May (Henry 2009). During its flowering period, the fluvial discharge from rivers to sea is almost negligible, and this would result in increased salinity of seawater. Qureshi (1993) reported that increased salinity of seawater prevents fruiting and causes senescence of immature flowers and buds. Henry (2009) stated that such a situation exists in the month of May when *A. annulata* ceases its flowering. *A. rotundifolia* displays certain distinct floral characters such as morning anthesis, lacking odor, short-tubed corolla with anthers at the rim of the corolla, placement of style and stigma slightly below the anthers, and production of hexose-rich nectar with high sugar concentration. These characteristics have been attributed to melittophily. Accordingly, this species is pollinated exclusively by honey bees and stingless bees, which affect both self-pollination and cross-pollination. Naskar and Mandal (1999) mentioned that this plant is pollinated by the honey bee*, Apis dorsata,* in the Sundarban mangroves. Bhattacharya et al. (2006) also noted that the pollen of this plant is dominant in honey collected from the Sundarbans region. Therefore, *A. rotundifolia* is primarily melittophilous.

Naskar and Mandal (1999) reported that in *A. rotundifolia*, the ovary is 5-carpelled and syncarpous, and stigma is absent in *A. rotundifolia*. But, Henry (2009) reported that *A. rotundifolia* produces 1-chambed ovary with a single ovule, but the ovary is extended into five styles and each style terminated with an extended oblique peltate stigma as reported by Tomlinson (1986). The fruit with hypocotyl inside grows upwards, and the entire fruit falls off; the fruit pericarp is essential for the hypocotyl to float in tidal water for dispersal.

3.4 Non-Viviparous Species

3.4.1 Genus Lumnitzera *(Combretaceae)*

Lumnitzera is a non-viviparous Indo-West Pacific mangrove genus of two evergreen tree species with similar vegetative appearance, *L. littorea* and *L. racemosa*. Both species occur in Cambodia, India, Indonesia, Malaysia, China, New Guinea, Philippines, Singapore, Sri Lanka, Thailand, Vietnam, and northern Australia and on various Pacific Islands (Shu 2007). In China, *L. littorea* grows in landward high salinity areas, often in association with *Avicennia marina, Clerodendrum inerme, Excoecaria agallocha, Scyphiphora hydrophyllacea,* and *L. racemosa*. It is an endangered species distributed in very restricted regions of Hainan province (Su et al. 2007).

L. littorea: The floral characters such as red flower color and the presence of abundant nectar accumulated at one side of the calyx tube indicate that the plant is adapted for bird-pollination. The flowers are longer, and the petals are directed forward, orienting the bill of the bird and protecting the nectar from most insects. The stamens are directed forward to touch the bill of the bird. The terminal inflorescences accommodate large pollinators. The plant is pollinated predominantly by honeyeaters such as *Meliphaga gracilis*, sunbirds, bees, and wasps (Tomlinson et al. 1978). Su et al. (2007) reported that *L. littorea* is an out-crossing species. Tomlinson et al. (1978) reported that in *L. littorea*, the flowers borne in terminal inflorescences are red, erect, and slightly zygomorphic, effectively lengthening the tube somewhat and providing some protection from short-tongued insects. These floral structural characteristics are adapted for bird pollination. In line with this, the flowers are predominantly pollinated by sunbirds and honeyeaters and are also additionally visited by bees and wasps. Details of pollination and fruiting ecology of this species are not available.

L. racemosa: It is characteristically a landward mangrove species occurring from eastern Africa to Tonga in the Pacific and northern Australia (Su et al. 2006). It grows in open remnant mangrove forests along seashores, estuaries, lagoon sides, saltwater swamps, and swampy meadows on sandy soils. It has two varieties namely var. *racemosa* with white flowers and var. *lutea* with yellow flowers; the former occurs throughout the range of the species, while the latter is confined to Timor Island of Indonesia (Shu 2007). In India, it is an interior mangrove growing luxuriantly in certain pockets of coastal belts of Kerala in India, characterized by infrequent tidal action, varied salinity and low water turbulence (Murugan et al. 2004). Further, it is reported to be present on the coastal belts of India and in Andaman and Nicobar Islands (D'Souza et al. 2010).

Tomlinson et al. (1978) reported that *L. racemosa* flowers from October to March in Queensland mangrove forest. Solomon Raju et al. (2014) reported that *L. racemosa* flowers massively and synchronously for 1 month only during mid-July to mid-August in India. Given the short-flowering season, the synchronous massive flowering pattern at population level is advantageous for this species to attract a wide variety of insects, which otherwise visit other co-flowering plant species. Tomlinson et al. (1978) noted that *L. racemosa* may be self-compatible and suggested that experimental work is needed to confirm this. Solomon Raju et al. (2014) reported that *L. racemosa* has a mixed breeding system that facilitates self-pollination and cross-pollination, but the latter mode is the pre-dominant mode through which highest fruit set occurs. Furthermore, the plant is capable of setting fruit through spontaneous autogamy by gravitational pollination, which, on sunny days, occurs due to the fall of powdery pollen grains from the dehisced anthers onto the papillose stigma that is situated slightly below the upper whorl of anthers. On rainy days, the rain drops/water falling in the flowers contributes to autogamy by gravitational pollination. The flowers are morphologically bisexual but functionally temporally dioecious due to protandry (on day 1) dry and non-receptive state of the stigma on the day of anthesis and stigma receptivity on the second and third day. The fruit set occurs through spontaneous autogamy. Tomlinson et al. (1978) stated that in *L. racemosa*, the pollen is present in the anthers only on the day the flower opens, while the stigma appears to be receptive on the second and subsequent days. Solomon Raju et al. (2014) reported that individual flowers are capable of self-pollination due to gravitational pollination, and it is substantiated by the occurrence of fruit set in bagged flowers of *L. racemosa*. Natural fruit set rate is very high, and it is a result of the function of all modes of pollination and fructification of fertilized flowers nourished by a resource-rich environment. Similarly, Tomlinson et al. (1978) also stated that fruit set in *L. racemosa* is high, probably over 50% in many trees, and even on isolated individuals, with all the flowers in a head setting fruit.

The floral characters in *L. racemosa*, such as actinomorphy, the white spreading petals and small volume of nectar secreted in the shallow calyx cup and easy accessibility of nectar to flower foragers due to broad and spacious corolla tube indicate entomophilous pollination syndrome (Solomon Raju et al. 2014). *L. racemosa* is frequently visited by wasps, bees, butterflies, and diurnal moths. Of these insects, wasps are the most common foragers and also aggressive in chasing the other flower visitors foraging simultaneously on the flowers.

In *L. racemosa*, the fruits are invariably 1-seeded despite the production of 3–5 ovules in the ovary of flowers suggesting that it is an inherent character of the plant to produce a single seed per fruit (Tomlinson 1986). Despite the highest natural fruiting rate in this species, its natural regeneration is low, which could be because a high percentage of mature fruits abort and because embryos are eaten by small grubs laid by insects early in fruit development. Ye et al. (2004) reported that in normally formed fruits of *L. racemosa*, the embryo is well protected by the hard layer of sclerenchyma tissue inside the outer corky or fleshy layers of the fruit wall. Fallen mature fruits become fibrous after floating in water. *L. racemosa* fruits dispersed by water lose the softer outer layers and expose the sclerenchymatous fibers and hence floating fruits lose their viability (Tomlinson 1986). This could be the reason for the failure of normal fruits of *L. racemosa* to germinate and produce new plants. Selvam (2007) experimentally proved that the germination rate of seeds of *L. racemosa* decreases with increasing salinity. The regeneration from normal seeds of *L. racemosa* that anchor in the sediment is relatable to salinity levels, which vary widely in mangrove environment (Solomon Raju et al. 2014). Erratic and insufficient rainfall due to climate change appear to be increasing salinity levels due to reduced outflows of freshwater from river water bodies into the sea. Tomlinson (1986) and Selvam (2007) suggested that fruits of *L. racemosa* are to be collected directly from parental trees and stored in wet conditions for 3–5 days before sowing in suitable locations. Such fruits germinate fairly readily, which indicates that the regeneration rate from the fruits of *L. racemosa* can be increased artificially.

Hamrick et al. (1991) stated that geographic range of any plant species is strongly associated with the level of variation maintained at the species level. Breeding systems, vegetative reproduction, and pollinators also significantly influence the genetic diversity of a species. Widely distributed plant species tend to maintain more variation than more narrowly distributed ones. *L. littorea* covers a wide geographic range throughout the Indo-Pacific region, but it is restricted only to Hainan region in China. The genetic variation in *L. littorea* is low at a population level in China in contrast to the high variation detected at the species level (Su et al. 2007). *L. racemosa* has two large populations in two forest reserves of Coringa mangrove forest in the State of Andhra Pradesh but has lost populations in all other areas nearby as is indicated by the scattered occurrence of only a few individuals, which is attributed to the effects of natural calamities such as cyclone, storm and flood, and man-made threats such as grazing by cattle and goat, overexploitation of juvenile fishes, felling for timber and firewood, human inhabitation, and pollution (Solomon Raju et al. 2014).

3.4.2 Genus **Excoecaria** *(Euphorbiaceae)*

The genus *Excoecaria* has 35 to 40 species found in tropical Africa and Asia eastward onto the islands of the Western Pacific. It is distinguished from closely related members of this group by a combination of characters such as dioecious condition, axillary inflorescences, male flowers with three stamens, and the absence of a caruncle from the seed. *Excoecaria agallocha, E. dallachyana,* and *E. indica* are found in mangroves. Of these, the last two species have not been investigated for their pollination biology.

E. agallocha: It is distributed from East Africa, India, and Ceylon to Hainan and the Ryukyu Islands through Malesia and Papuasia, including tropical Australia and into the Pacific as far as Niue and Samoa. *E. agallocha* is an evergreen mangrove tree often bordering mangrove swamps, a dioecious, obligate out-crosser and appears to be bee-pollinated (Tomlinson 1986). *E. agallocha* is a semi-deciduous tree species distributed in oligohaline to polyhaline zones of the mangrove forest, it flowers during the rainy season, and flowering is synchronous in both male and female trees (Henry 2009). The ratio of male to female trees is 2.2:1, while the ratio of male to female flowers at inflorescence level is 16:1. Both sexes of flowers are small and lacking odor; the anthers in male flowers are free, exposed, and versatile, the conditions of which facilitate the release of pollen into the air and occurrence of anemophily (Henry 2009).

The long catkins of male trees and the short, mixed cymes of female trees are quite attractive to foragers. The yellow stamens of male flowers and bright green shining styles of female flowers further enhance attractiveness to foragers. Both the flower sexes produce nectar; it is traces in male flowers, while it is relatively measurable in female flowers. These characteristics indicate that the plant is also evolved for pollination by insects. The flowers are pollinated by bees, flies, and butterflies. Therefore, the plant is evolved for pollination by both wind and insects indicating the function of ambophily, which enables the plant to colonize different salinity zones within the mangrove forest (Henry 2009).

In *E. agallocha*, fruit is set is more than 90% and each fruit is invariably 3-seeded (Henry 2009). Seeds lack dormancy and are released explosively from the mature dry fruit capsules Das and Ghose (2003). The released seeds settle and produce new plants within the parental sites if the floor is exposed and if not, seeds with an air space inside float in tidal water and establish new populations in different salinity zones of mangrove forest (Henry 2009).

3.4.3 Genus **Barringtonia** *(Lecythidaceae)*

The genus *Barringtonia* has 56 species, which are widely distributed in the tropical regions from eastern Africa to northern Australia (Tanaka 2004). However, Prance (2012) revised this genus and recognized 69 species with three distinct areas of species diversity, namely the Malay Peninsula, Borneo, and New Guinea. Only three species, *B. asiatica, B. acutangula,* and *B. racemosa,* are extremely widespread and occur in lowland areas near the sea or beside streams and dispersed by water. *B. racemosa* is a coastal species that flourishes well under humid and moist conditions and is distributed along tropical and sub-tropical coasts in South Africa, Mozambique, Madagascar, India, Sri Lanka, Malaysia, Thailand, Laos, southern China, northern Australia, coastal Taiwan, the Ryukyu Islands, and Polynesian Islands (Chantaranothai 1995). Boo Chich et al. (2006) noted that *B. racemosa* is rare in the wild and occurs in damp places in mangroves, tidal rivers, sandy and rocky shores, and freshwater swamps in Singapore where it is listed as Critically Endangered on the Red List of threatened plants of Singapore (Keng et al. 1998). In India, it is distributed on the west coast from Konkan southwards through Karnataka, Kerala, Tamil Nadu, Sundarbans, and in the Andaman and is actually a common and major species in the estuary adjacent to Poovar Island (Mahanti and Kumar 2017) but is becoming very rare in other Indian mangrove forests due to conversion and modification of landward areas (Solomon Raju et al. 2019).

Few workers have reported different aspects of pollination biology of this species from different regions of the world, while there is no published information on the pollination biology of all other *Barringtonia* species. *Barringtonia racemosa* is an evergreen tree species with a brief period of leafless condition during dry season and flowering throughout the year. The flowers are pinkish-white borne on long, racemes, and quite attractive from a very long distance. The flowers produce copious amount of nectar and strong scent at night, which attracts both moths and bats in South Africa (Strey 1976). Marshall (1983) reported that *B. racemosa* is bat-pollinated on Iriomote Island of Japan, but 20 years later Tanaka (2004) found the bats extinct and suggested were now pollinated by moths. Solomon Raju et al. (2019) reported that *B. racemosa* shows anthesis during night time; this trait and other floral traits such as long and brush-like flowers on long hanging racemes, strong sweet odor emitted from the flowers upon anthesis, and moderate quantity of semi-dilute nectar characterize the moth pollination syndrome. Ants, *Camponotus,* and *Oecophylla* spp. crowd the flowers and racemes after shedding the petals and stamens and feed on the left-over nectar placed around the ovary (Strey 1976; Solomon Raju et al. 2019). Although ants have no role in pollination, their presence may deter insects that cause harm to the ovary.

B. racemosa produces fruits with a single seed, which is enclosed by spongy and fibrous flesh (Van Wyk and Van Wyk 1997), which provides them buoyancy and allows them for dispersal in tidal water (Solomon Raju et al. 2019). Since the fruits are indehiscent, the seed remains inside and germinate only when the fruit rots and settles in the muddy substratum. After the seed anchors in the substratum, it germinates within 2–3 weeks and gradually produces a new plant.

3.4.4 Genus **Xylocarpus** *(Meliaceae)*

The genus *Xylocarpus* is the only mangrove in the Meliaceae family (Filippos 2018). It has three distinct moderate-sized evergreen or deciduous monoecious or dioecious tree species with well-developed woody trunks yielding valuable timber. They are *X. granatum, X. mekongensis,* and *X. moluccensis*; all the three species are distributed in the tropical tidal forests of the Old World, typically in the mangrove habitat or in sandy or coastal habitat spreading from Africa to Australia through India and Malayan Archipelago (Tomlinson 1986). Several authors (Singh and Garge 1993; Banerjee and Rao 1990; Banerjee et al. 1989; Deshmukh 1991) stated that all three species of *Xylocarpus* occur on Andaman Islands and Orissa coast, while *X. granatum* and *X. mekongensis* occur in the Sunderbans and Tamil Nadu coast. Kathiresan (2003) reported that *X. mekongensis* is restricted to West Bengal, Orissa, and Andaman, while *X. moluccensis* is restricted to Andaman. *Xylocarpus* species are threatened in India (Kathiresan 2008), and *X. granatum* is a critically endangered species of Maharashtra and disappearing from many locations and represented by only a few individuals (Jugale et al. 2009).

3.4.4.1 *X. granatum* and *X. mekongensis*

Xylocarpus is monoecious with morphologically bisexual but functionally unisexual flowers, which are pollinated by bees (Tomlinson 1986). Mangrove honey samples in Sundarbans (Bangladesh) and Little Andaman (India) contained *X. granatum* pollen suggesting that honey bees use this species as a pollen source (Venkatesan 2011). Almazol and Cervancia (2013) reported that *X. granatum* is an obligate outcrosser and has moth-adapted floral traits and is principally pollinated by moths, while flies act as supplementary pollinators in the Philippines. Bees such as *Xylocopa* sp., *Apis dorsata,* and *A. cerana* visit this species; the first two species being large-bodied have difficulty to probe the flower because the cup-like structure of the corolla and the location of anthers act as a barrier for them to make entry into the flower either to collect pollen or nectar. However, *A. cerana* being smaller in size penetrates into the interior of the corolla tube to collect pollen and pollinates the flowers of *X. granatum*. Solomon Raju (2020) reported that both *X. granatum* and *X. mekongensis* with simultaneous flowering and similar floral architecture and morphology attract the same species of flower foragers to their flowers. In both species, hawk moths are the principal pollinators, while bees and butterflies are the supplementary pollinators. The two plant species with almost synchronous flowering and common insect pollinator fauna have possibilities to receive pollen from each other by their stigmas. Each of these plant species is likely to experience stigma clogging by the pollen of other species, and such a situation could reduce the chances for pollination by the compatible pollen. Further, there is also a possibility for cross-pollination between *X. granatum* and *X. mekongensis* if inter-specific pollen is compatible to both.

X. granatum in the Philippines displays two or three flowering seasons in a year (Almazol and Cervancia 2013), whereas that in India flowers throughout the year on the Orissa coast (Banerjee and Rao 1990; Upadhyay and Mishra 2010). Raju (2003) reported that *X. granatum* and *X. mekongensis* are distinguishable by their root, trunk, bark, leaves, inflorescence, and fruit characters in the field. Both species are seasonal bloomers; the former is an evergreen species and blooms during August–September, while the latter is a deciduous species and blooms during June–July in Coringa Mangrove Forest, Andhra Pradesh, India. Solomon Raju (2020) reported that both *X. granatum* and *X. mekongensis* are semi-evergreen species and exhibit leaf fall, leaf flushing, flowering, and fruiting aspects sequentially without any time gap. They are seasonal bloomers with flowering during June–August, but sporadic flowering also occurs on certain branches of individual plants outside this flowering season except April–May. Furthermore, the fruiting season is well defined and mature fruits disperse seeds in October. However, sporadic flowering contributes to the production of fruits by the plants almost throughout the year. As a result, seasonal flowering and aseasonal sporadic flowering make the plants to display floral bud initiation, flowering, fruit initiation, and maturing and mature fruits throughout the year.

Xylocarpus produces 3-flowered cymes with the terminal flower often female, which opens first, while the lateral flowers are male, which open later. Female flowers produce sterile pollen, while male flowers produce non-functional ovules (Tomlinson 1986). Solomon Raju (2020) reported that *X. granatum* and *X. mekongensis* produce axillary paniculate 3-flowered cymes with the terminal flower usually pistillate, which opens first, while the lateral ones usually staminate, which open later. *X. mekongensis* produces solitary flowers between 3-flowered cymes, and these flowers are usually pistillate. In both species, the pistillate and staminate flowers produce stamens with dehiscent anthers, but pollen is fertile in staminate flowers only. The two flower sexes produce ovary with ovules, style, and stigma, but only pistillate flowers have well developed ovary with functional ovules. The terminology of "male" and "female" for flower sexes in these species is irrelevant because all flowers have both male and female sex organs. Since the pistillate and staminate flowers differ only in the functionality of sex organs and display morphological similarity with each other, there is remote possibility for pollinator insects to discriminate between the two flower sexes prior to flower visitation. Further, both flower sexes produce minute drops of nectar as reward for the appropriate flower visitors. Morphological similarity in flower structure, shape, calyx and corolla traits, and production of scent and nectar by both flower sexes facilitates pollinator insects to visit both sexes without any discrimination and transfer pollen from staminate to pistillate flowers with pollination as end result. In both species, the production of pistillate and staminate flowers in the same inflorescence and plant indicates that these species are morphologically hermaphroditic but functionally monoecious and exclusively pollinator-dependent.

Almazol and Cervancia (2013) reported that *X. granatum* shows anthesis during 1800–2200 h and the flowers remain open until 1000 h on the next day. Solomon Raju (2020) reported that the *X. granatum* and *X. mekongensis* show anthesis during 1600–1830 h. Individual plants produce pistillate and staminate flowers daily either on the same or different inflorescences, and simultaneous presence of both flower sexes does not preclude geitonogamy but facilitates the promotion of out-crossing as the longevity of pollen viability and stigma receptivity is extended until the evening of the next day. Individual plants have an unknown inherent regulatory mechanism to optimize fruit set rate to enable the inflorescence to hold the growing fruits until maturation and seed dispersal because of their heavy weight. The brittle nature of inflorescences also does not enable to hold several heavy mature fruits. Further, production of low fruit set rates is attributed to the production of a few pistillate flowers per inflorescence and/or plant. Sporadic flowering in both *X. granatum* and *X. mekongensis* could be an evolved strategy to produce more fruits to compensate the low fruit set that comes from the actual fruiting season (Solomon Raju 2020).

3.4.5 *Genus* Scyphiphora *(Rubiaceae)*

Scyphiphora is a monotypic genus represented by *S. hydrophyllacea* belonging to the family Rubiaceae. It is an uncommon constituent of mangroves and distributed from southern India and Sri Lanka throughout Southeast Asia to northern Australia and western Polynesia (Solomon Islands). It occurs in muddy, sandy, and rocky substrates on the landward margin of mangroves or on the banks of tidal waterways. It is intolerant of lengthy periods of freshwater inundation and usually occupies sites that are frequently inundated by the tides (Heyne 1950; Tomlinson 1986; Wim et al. 2006; Tao and Charlotte 2011). The species has been reported to be declining in many regions primarily due to extraction and coastal development and appears in small numbers in most areas of its range (Ellison et al. 2010). It is considered rare in India (Ramasubramanian et al. 2003) and a highly threatened species in Sri Lanka (Hettiarachchi et al. 2002).

Scyphiphora hydrophyllacea is a non-viviparous evergreen tree species that can flower throughout the year (Wim et al. 2006). Almazol and Cervancia (2013) noted that in the Philippines, it flowers from February to June with peak flowering period during March–May and a few inflorescences in certain trees bloom after this regular flowering season and fruiting occurs during April–October. In India, concentrated flowering is during June–August and flowering outside this period is very sparse and occurs only on certain trees. Fruiting occurs throughout the year depending on the production of flowers on the plant but peak fruiting occurs during July–September (Solomon Raju and Rajesh 2014). The flowers are white tinged with pink color, nectariferous, odorless, bisexual, and markedly protandrous.

Puff et al. (1996) reported that secondary pollen presentation (SPP) occurs widely in all the sub-families of Rubiaceae. These authors recognized four types of SPP based on the pollen presenting area and receptive surface of style and stigma. In the first type, pollen deposition occurs on the style only and its deposition is strictly on non-receptive surfaces. In the second type, pollen deposition occurs on the style and outside of the stigma lobes; pollen is solely deposited on non-receptive surfaces. In the third type, pollen deposition occurs on the outer side of the stigma, while in the fourth type, it occurs exclusively, largely, or partly on the receptive surface of the stigma. Almazol and Cervancia (2013) mentioned that in *S. hydrophyllacea*, selfing may be promoted by the adherence of pollen on the outside of the style. Puff and Rohrhofer (1993) reported that the flowers of *S. hydrophyllacea* possess "Ixoroid" pollination mechanism representing second type of SPP in which the flowers are protandrous and deposit the pollen on the outside of the stigmas and style for dispersal. Solomon Raju and Rajesh (2014) also conform the function of the same mechanism, but these authors stated that during anthesis, pubescent hairs situated at the corolla mouth facilitate brushing of style and stigma against the dehisced anthers with certainty. In the stigma, the outer surface is non-receptive, while its inner surface is receptive on second and third days of flowering. Self-pollen deposition occurs along the margins of stigmatic lobes, and part of it enters through linear opening between them facilitating autogamy when the stigma is receptive. Pollen is viable on the second and even on the third days of the flower life, and it is confirmed by the occurrence of fruit set in bagged flowers. Almazol and Cervancia (2013) reported that fruit set is 100% in bagged and un-bagged treatments of *S. hydrophyllacea*; all fruits in un-bagged flowers matured, while fruits from bagged flowers are an indication of self-fertility, but they display high abortion rate indicating some inbreeding depression or poor nutrition. Solomon Raju and Rajesh (2014) also reported that in addition to SPP, anemophily is also functional because the location of the habitat of the species is windy most of the time, day and night.

S. hydrophyllacea exhibits a mixed mating system because of the occurrence of fruit set through all modes of pollination. Self-pollination within the flower is not vector-dependent, while self-pollination between flowers on the same or different individuals of this species requires external agents (Solomon Raju and Rajesh 2014). Different authors reported that *S. hydrophyllacea* is entomophilous or insect-pollinated or bee-pollinated (Tomlinson 1986; Wheeler et al. 1992; Selvam and Karunagaran 2004; Wim et al. 2006; Almazol and Cervancia 2013). The study by Almazol and Cervancia (2013) indicated that the plant is pollinated by a total of 15 insect species out of which only three were bee species, namely *Xylocopa* sp., *Apis dorsata,* and *Tetragonula biroi*. Solomon Raju and Rajesh (2014) reported that *S. hydrophyllacea* is exclusively pollinated by three bee species, *Apis dorsata, A. florea,* and *Nomia* sp. only. The peduncle of the inflorescence keeps the flowers in almost an erect position and supports the flowers to hold the larger foragers such as *Apis dorsata*. The reflexed petals serve as landing platform for the large insects (Almazol and Cervancia 2013).

S. hydrophyllacea self-pollinating ability without vectors is important to colonize an area and establish population in isolated localities (Solomon Raju and Rajesh 2014). The vector-mediated pollination facilitates the occurrence of genetic variation that is essentially required for adaptation to changing edaphic and physical environments. The mixed mating system is advantageous for the plant to adapt itself to the characteristic harsh environments of mangroves. Despite the ability to set fruit through self-pollination and cross-pollination, the plant is unable to regenerate itself due to total absence of seed germination. Similarly, Hettiarachchi et al. (2002) reported that in Sri Lanka, *S. hydrophyllacea* produces fruits, but seedlings and young plants are absent. It produces very low percentage of seed bearing fruits and an inability to produce healthy seedlings and hence is highly threatened throughout the world. This is attributed to a genetic disorder in the seed due to inbreeding depression in isolated small populations. The presence of self-sterility and the absence of pollinators might be some other reasons. On the contrary, Almazol and Cervancia (2013) mentioned that seed germination occurs from the fruits of both bagged and un-bagged flowers of *S. hydrophyllacea* in the Philippines. These authors also stated that seed germination is significantly higher from the fruits of un-bagged flowers, but overall germination is below 20%.

3.4.6 Genus Sonneratia *(Sonneratiaceae)*

The Sonneratiaceae family comprises only two small genera, *Sonneratia*, which extends from tropical eastern Africa and adjacent islands to Queensland of Australia, Micronesia and Melanesia, and *Duabanga*, which is confined to southeastern Asia. *Sonneratia* is a genus of trees of mangrove swamps and seacoasts generally, and the inland genus *Duabanga* is an evergreen component of the rainforest belt (Backer et al. 1954). *Sonneratia* is a typical constituent of mangrove communities throughout its range, often forming a seaward fringe. It has five evergreen hermaphroditic species, *S. alba, S. caseolaris, S. ovata, S. apetala,* and *S. griffithii* (Duke and Jackes 1987). However, Shi et al. (2000) classified into two sections, *Sonneratia* and *Pseudosonneratia*, based on the presence or absence of petals. The section *Sonneratia* includes *S. alba, S. caseolaris,* and *S. paracaseolaris* that have petals. The section *Pseudosonneratia* includes *S. apetala, S. ovata, S. hainanensis,* and *S. griffithii* that lack petals. In all, except *S. paracaseolaris* and *S. hainanensis*, the flower buds enlarge rapidly and open during the early evening hours, the style at first projecting and the recurved stamens with powdery pollen expand abruptly as the calyx segments diverge producing copious amounts of nectar from a basal disk and emitting a sour, butter-like odor.

Sonneratia is bat-pollinated, as the floral characteristics such as evening anthesis, expansion of calyx exposing the mass of extended stamens with powdery pollen, and the production of a quantity of nectar at the basal disk and falling of stamens by the next day are adaptations (Tomlinson 1986; Start and Marshall 1976). In Peninsula Malaysia, large limestone caves provide roosting areas for bats and the bat pollination in *Sonneratia* in this region might have evolved between them over a period of time. Furthermore, hawk moths also pollinate *Sonneratia* (Primack et al. 1981; Tomlinson 1986).

3.4.6.1 *S. caseolaris*

S. caseolaris is protogynous and herkogamous; it is pollinated by nocturnal moths and mammals during night and by butterflies, bees, wasps, flies, and birds during daytime in the mangrove forests of Orissa, India (Pandit and Choudhury 2001). Tomlinson (1986) noted that fruit set is poor, but seed set is high. Pandit and Choudhury (2001) reported that in *S. caseolaris*, each fruit produces numerous seeds, and this character may enable the plant to withstand the pressure of predation because of the high rate of seed set in the surviving fruits.

3.4.6.2 *S. apetala*

S. apetala is a dominant species in mangrove communities of India, Bengal, and Sri Lanka (Jayatissa et al. 2002) in 40% of the sampled sites but locally extinct in some parts of South India and rare in Andaman and Nicobar Islands (Kathiresan 2008). *S. apetala* is a seaward polyhaline evergreen tree (Selvam and Karunagaran 2004) or euhaline, tolerant of high salinities and regulates salt levels by salt exclusion (Tomlinson 1986). In *S. apetala,* flowering and fruiting occur during July–November (Ramasubramanian et al. 2003). The flower buds of *S. apetala* enlarge rapidly and open during the early evening, the style at first projecting and the recurved stamens with powdery pollen expand abruptly as the calyx segments diverge and expand. The flowers produce copious amount of sucrose-rich nectar from a basal disk and emit a sour, butter-like odor, and the stamens mostly fall from the flower on the next day; all these characters indicate adaptations for bat-pollination according to Faegri and van der Pijl (1979). However, Henry (2009) reported that *S. apetala* has not been visited by bats, nocturnal moths, and day-active insects in Coringa mangrove forest, Andhra Pradesh, India. This author attributed the total absence of foraging activity of biotic agents to the presence of high winds at the plant site and non-availability of roosting sites for bats. Fruit set in this species is reported to be a function of anemophily. The flowers being large, distinct against the foliage, exposing the numerous stamens to air, and the high pollen output per flower and the powdery pollen enable anemophily to be effective to set fruit in this species.

S. apetala is weakly protogynous, herkogamous, self-compatible, and self-pollinating and cross-pollinating with highest fruiting rate in the latter mode of pollination, but fruit abortion rate is significant, which might be an indication of selective elimination of the growing offspring, especially those originating from selfing to allocate resources for the xenogamous fruits (Henry 2009). Moreover, *S. apetala* flower produces numerous ovules, but only about 25% of them set seed in each fruit and fruit set rate exceeds 60%. Parakeets act as fruit predators of *S. apetala* by feeding on the pulpy pericarp without causing any damage to seeds. Das and Ghose (2003) reported that *S. apetala* fruit is indehiscent and its small angular seeds release following the decay of the fruit pulp or pericarp. Ren et al. (2009) reported that *S. apetala* has high adaptability to saline conditions. Terrados et al. (1997) noted that *S. apetala* is a fast-growing species and hardy, but the seed viability period is less than 3 months. It is capable of forming monotypic stands and is a pioneer species that colonizes on newly formed mudflats. However, *S. apetala* is experiencing regeneration problems in Coringa mangrove forest, where it is located on the seaward side where there is high salinity year round (Henry 2009).

3.4.6.3 *S. alba*

S. alba is a euhaline seaward evergreen tree species (Selvam and Karunagaran 2004). The flowering season has been reported differently by different authors. Ramasubramanian et al. (2003) reported that *S. alba* shows flowering and fruiting events during February–October in Coringa mangrove forest, Andhra Pradesh, India. In the same forest, Henry (2009) reported that *S. alba* blooms from May to August. But, Suvarna Raju (2011) reported that *S. alba* flowers for only 2 weeks in

August in the same forest. The flowers have petals, but they are inconspicuous. However, the petals appear to be serving as sealant of calyx basal cup as well as its lobed part during bud stage. The flower buds enlarge rapidly and open during the early evening, the style at first projecting and the recurved stamens with powdery pollen expand abruptly as the calyx segments diverge and expand. The flowers produce a moderate volume of nectar and emit a butter-like odor, and the stamens fall off by the evening of the second day of flowering life.

The floral scent of *S. alba* consists of several chemicals of which the presence of 2,4-dithiapentane suggests that the species may be bat-pollinated, while other chemicals present in the scent may attract several types of nocturnal visitors such as moths (Azuma et al. 2002). Suvarna Raju (2011) reported that *S. alba* flowers display bat pollination traits such as early evening anthesis, horizontal or downward hanging position, and emission of butter-like odor. But this tree has never been visited by bats, nocturnal moths, and day-active insects. The other floral characters such as large-sized flowers, production of numerous stamens exposed to air, the production of high pollen output per flower, high pollen-ovule ratio, and the powdery pollen facilitate the occurrence of anemophily. The natural fruit set is very low, but it is compensated by high seed set rate. Rhoades and Bergdahl (1981) noted that in *S. alba,* 50% of flower buds abort due to attack by a weevil of Attelabidae, Rhynchitinae, whereas Suvarna Raju (2011) reported flower bud abortion is completely absent. Rhoades and Bergdahl (1981) also documented that possums, rats, and parrots serve as predators of flowers of *S. alba*, but Suvarna Raju (2011) reported that flower predation is completely absent and the seeds disperse following the decomposition of the fruit in tidal water.

3.5 Conclusions

The sexual system, mating system, pollen discharge mechanism, pollinators, and seed set per fruit, and the unit of propagule for all the three groups of mangrove plant species detailed in this review are presented in Table 3.1. In Rhizophoraceae, the mangrove genera show different pollen discharge mechanisms that are adapted to different classes of pollinators. *Rhizophora* spp. flowers are nectarless, while the flowers of other genera are nectariferous. In *Bruguiera* spp. and *Ceriops tagal*, the pollen discharge mechanism is explosive, highly specialized, and vector-dependent and requires multiple visits by pollinators for pollen discharge from each pair of stamens enclosed by individual petals, while it is non-explosive, not specialized, and not exclusively vector dependent in *Kandelia candel* and *Ceriops decandra*. In *Rhizophora* spp., the pollen discharge mechanism is also non-explosive, not specialized but the floral traits indicate adaptations for anemophily. Pollinators include birds, bees, and butterflies in *B. gymnorrhiza*, bees, wasps, and butterflies in *B. cylindrica*, bees, wasps, and flies in *C. decandra*, bees, butterflies, moths, flies, and wind in *C. tagal* and beetles, thrips, bees, and butterflies in *K. candel*. *R. apiculata* and *R. mucronata* with floral traits adapted for pollination by wind are also pollinated by thrips, bees, and moths. All Rhizophoraceae mangroves display mixed breeding systems, which involves autogamy, geitonogamy, and xenogamy, but high fruit set rate occurs in the last two modes only.

In crypto-viviparous mangroves, the pollen discharge mechanism is not explosive or specialized; the floral traits in individual species indicate generalized adaptations for entomophily, and pollinators are offered both pollen and nectar as floral rewards. Pollinators include beetles, bugs, bees, bee flies, wasps, ants, flies, butterflies, and moths in *Avicennia*, bees, wasps, flies, and butterflies in *A. corniculatum* and bees in *A. rotundifolia*. Birds and wind also have a role in the pollination of *A. corniculatum*.

In all non-viviparous mangroves except *E. agallocha* and *S. hydrophyllacea*, the pollen presentation or discharge mechanism is not explosive or specialized. The floral traits in each species indicate generalized adaptations for either entomophily or zoophily or both. *E. agallocha* has floral traits adapted mostly for anemophily, while *S. hydrophyllacea* has a specialized secondary pollen presentation mechanism that facilitates autogamy. In all these species, the flowers are nectariferous and offer both pollen and nectar as rewards. Pollinators include birds, bees, and wasps in *L. littorea*, wasps, bees, butterflies, and diurnal moths in *L. racemosa*, moths and bats in *B. racemosa*, bees and moths in *X. granatum* and *X. mekongensis*, bees in *S. hydrophyllacea*, and mammals, birds, bees, wasps, flies, and butterflies in *S. caseolaris*. In *E. agallocha*, anemophily is the principal pollination mode, but with its nectariferous male and female flowers, it is also pollinated by bees, flies, and butterflies. *S. hydrophyllacea* with entomophilous floral traits is also pollinated by wind. *S. apetala* and *S. alba* with entomophilous floral traits have become anemophilous in the seaward habitats where pollinators are not available. Of these, *E. agallocha* and *Xylocarpus* are vector-dependent, while all other species although vector-dependent have the ability to fruit through autogamy.

All mangrove species examined except *Xylocarpus* and *E. agallocha* are hermaphroditic with mixed mating systems, self-compatible and self-pollinating. *Xylocarpus* is monoecious, while *E. agallocha* is dioecious; both species are obligate out-crossers. *Sonneratia* is weakly protogynous, while all other mangroves are weakly protandrous. *Bruguiera, C. tagal*, *Xylocarpus,* and *E. agallocha* are obligately vector-dependent. The mixed mating system functional in all other hermaphroditic species ensures the production of fruit/seed in the presence or absence of pollinating agents and facilitates self-propagation in new habitats within the mangrove forest.

In all viviparous and crypto-viviparous species, and non-viviparous species, *Lumnitzera* and *B. racemosa*, fruits are characteristically 1-seeded irrespective of the number of ovules produced by flowers. In *E. agallocha* and *S. hydrophyllacea*, all ovules produced in individual flowers form seeds if fertilized. Fruits are 8–12-seeded in *X. granatum* and 5–8-seeded in *X. mekongensis* irrespective of the number of ovules produced by flowers. In *Sonneratia,* the fruits are many-seeded and increase seed set rate depending on the number of ovules fertilized and energy resources available during fruiting phase. In viviparous mangroves, hypocotyls produced from the seeds of *Bruguiera, C. tagal,* and *K. candel* grow downwards, while those produced from the seeds of *C. decandra* and *Rhizophora* spp. grow upwards. The hypocotyls protrude out of the fruit pericarp, become naked, and show different stages of growth in viviparous mangroves, while they remain inside the fruit in crypto-viviparous mangroves. In both viviparous and crypto-viviparous mangroves, the hypocotyl is the propagating unit, while in non-viviparous mangroves, seed is the propagating unit. All categories of mangroves employ self-planting and stranding strategies according to the tidal conditions for the recruitment of new plants and populations across salinity gradients within the mangrove forest.

Therefore, the reproductive ecology of mangrove plants is important to understand how and to what extent their sexual reproduction is dependent on pollinator fauna or wind in order to successfully reproduce, populate, and expand their distribution range within the mangrove ecosystem. The knowledge of reproductive ecology of mangrove plants accumulated so far indicates that the spectrum of their pollinators is broad, and no plant is highly dependent on one specific pollinator, and the plants are specialized only to the extent of being associated with a given class of pollinators. Such flexibility in utilizing different pollinator species is highly advantageous and adaptive for mangrove plants so that they are not constrained by a dependence on a specific pollinating agent with a limited geographic range. Since each mangrove plant species adapts primarily to a generalized type of pollinator, competition for the available pollinator resources is reduced. This knowledge forms the baseline information to carry out further studies on how successful mangroves are at utilizing pollinators, how much reproductive effort is required to produce individual propagules, and whether propagule production is constrained by pollinator or nutrient resources. Further, detailed studies on the reproductive ecology of mangrove plants throughout their distribution range are required to understand in the holistic way the success of sexual reproduction in relation to pollinator fauna available in the ecosystem in order to take effective measures for the restoration, rehabilitation, and management of mangrove ecosystems.

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Chapter 4
Mangrove Health Analysis Using Multi-Temporal Sentinel-2 Multi-Spectral Instrument (MSI) Data

Dibyendu Dutta, Tanumi Kumar, Chiranjivi Jayaram, and Pragyan Jain

Abstract In this study, two pigment indices, viz. Normalized Difference Vegetation Index (NDVI) and Normalized Difference Chlorophyll Index (NDCI), and one canopy moisture index (Normalized Difference Moisture Index, NDMI) have been generated using the Sentinel-2 bands to examine the spatiotemporal variability of mangrove health of the Sundarbans. Vegetation indices employing the red-edge bands of Sentinel-2 are able to provide an additional information on leaf and canopy structure and early detection of stress. Higher spatial and temporal resolution during post-monsoon season revealed micro-level variability in canopy chlorophyll and moisture status of the integrated Sundarbans of India and Bangladesh. Based upon a review of literature, first-time red-edge bands have been used for Sundarbans mangrove health mapping. The multi-temporal data of November 2020–April 2021 reveal significant difference in the canopy chlorophyll wherein in the eastern part of the Sundarbans (Bangladesh region) viz. the Sarankhola, south of Chandpal and Khulna ranges, and the northern tip of Khulna and Chandpal ranges exhibit good health, but the rest of the Sundarbans mostly have medium-to-poor chlorophyll content. In the Indian region, the islands/reserve forests that have medium values of vegetation indices include south of Baghmara, Gona, Mayadwip, Chhotahardi, Herobhanga, Jhilla, and Arbesi. In general, the highest values of the vegetation indices are attained during November and lowest during February–March. The canopy moisture, however, exhibited a contrasting feature while comparing with the pigment indices. The values of NDMI are low in the eastern part of the Sundarbans including most of Sarankhola, Chandpal, and the entire eastern part of the Khulna Range. The canopy moisture appears to be higher in the western half of the Sundarbans falling in the Indian region. These observations need further investigation in the field.

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4.1 Introduction

Mangrove forests, one of the most productive and unique ecosystems on earth (Donato et al. 2011), are mostly found in the tropical and subtropical regions along the coastlines, estuaries, and deltaic regions formed by river networks (Giri 2016). They are known for their high ecosystem and economical services values. The Sundarbans is the world's largest contiguous deltaic patch of mangrove ecosystem, formed by the fluvial deposits of three major rivers, the Ganges, Brahmaputra, and Meghna, and spans over two adjoining countries: India and Bangladesh. The mangrove has unique importance because of its ecosystem services, protective functions, biological productivity, and livelihood options for the large number of populations living in the fringes of the Sundarbans Biosphere Reserve (Naskar and GuhaBakshi 1987). The ecosystem plays a crucial role by acting as a bio-shield against storm surges and thereby helping to reduce the vulnerability to extreme climatic events like cyclones (Kathiresan and Bingham 2001). Extensive and deep-rooted system of mangroves helps in protecting coastline from erosion, and they also act as a nutrient filter and nursery grounds for coastal fishes (Rahman and Asaduzzaman 2010). Historically, 10% of global tropical cyclones occur in the Bay of Bengal (GOB, UNDP, World Bank 1993), of which one-sixth had landfall on the Sundarbans coast. Tropical cyclones at landfall regions cause extensive damage to mangroves, wildlife habitat, and human settlements in the adjoining forest areas due to the low and flat topography. During storm surges, brackish water intrudes deep inside the forest through creeks making the land highly saline and unsuitable for forest species sensitive to soil salinity. Moreover, frequent catastrophic disturbances may lead to a limited chance of recovery of mangrove vegetation due to nonavailability of mangrove propagules (Rashid et al. 2009). Hence, prolonged canopy gaps in the open areas are occupied by invasive species, which alter the existing physical environment and community of organisms at a particular site (Biswas 2003) causing cryptic ecological degradation. Climate change has considerably increased the intensity and frequency of tropical cyclones (Houghton et al. 2001; IPCC 2007), which affect the delta-building process. Furthermore, anthropogenic pressure (Giri 2016) for livelihoods further aggravates the vulnerability.

Hence, it is imperative to monitor the health of the mangrove vegetation periodically for ecological conservation, restoration, and developing forest management plans for sustainability of the vulnerable coastal regions of this delta. As most of the areas of the Sundarbans are either inaccessible or protected due to wildlife habitat, it is difficult to monitor the vegetation condition at regional and local scale by traditional means. Remote sensing from space orbit serves as a proxy to vegetation health through its bio-optical response. There are several broadband and narrow-band indices that are being used operationally for remote estimation of leaf chlorophyll concentration (LCC) and other biophysical parameters in conjunction with limited ground-based/laboratory observations. Although their accuracy is significant at leaf level, this is not so at canopy level due to the complex interaction of dry/green vegetation, soil, shadow, etc., within the sensors' footprint. Plant leaf chlorophyll is considered to be the most important pigment directly related to the photosynthetic capacity and net primary productivity (Croft et al. 2017). It is also an effective bio-indicator of plant growth condition, nutritional status, environmental stress, senescence, and disturbances (Korus 2013; Main et al. 2011). Hence, quantitatively monitoring the spatial–temporal variation of LCC could provide crucial information to understand the ecosystem response to the changes in environmental, meteorological, and ecological factors (Croft et al. 2017; Richardson et al. 2002). Traditionally, the leaf pigment, especially chlorophyll, is measured in a laboratory using destructive sampling, which is not only time-consuming but seldom represents the spatial variability and is difficult to upscale. With the availability of remote sensing sensors at an orbital platform, it is possible to monitor vegetation health at a wide range of spatial and temporal scales employing the reflected signal in the visible–near-infrared–shortwave infrared region. Several researchers have successfully investigated the remote estimation of leaf chlorophyll through statistical and physical methods (Ali et al. 2020; Houborg et al. 2015). Among different algorithms, viz. parametric [vegetation indices (VIs)], nonparametric, physically based, and hybrid methods, it has been found that the parametric regression method using VIs is most widely studied with various sensors of remote sensing (Croft et al. 2014). Improved VIs are continuously being evolved to minimize the soil background effect and also take into consideration the red-edge bands of green vegetation. The improved VIs are sensitive to the spectral characteristics of vegetation traits and help in minimizing the influence of background noises and canopy structure by spectral band combinations (Zhen et al. 2021).

In this study, two pigment indices, viz. Normalized Difference Vegetation Index (NDVI) and Normalized Difference Chlorophyll Index (NDCI), and one canopy moisture index (Normalized Difference Moisture Index, NDMI) have been used to examine the spatiotemporal variability of mangrove health of the Sundarbans. In both the pigment indices, red-edge bands of Sentinel-2 have been optimally used. Due to persistent cloud cover, the Sentinel-2 data on cloud-free days between November and April have been used.

4.2 Spectral Reflectance of Vegetation

The absorption and reflectance of different wavelength regions by vegetation are a result of a complex interaction of leaf/canopy biochemicals (e.g., chlorophyll-a and b and β-carotene) and intercellular structure of the leaf wherein multiple reflection of the incoming electromagnetic waves takes place. Healthy leaves absorb 70–90% of incident visible radiation, particularly in the blue and red wavelengths (centered around 450 nm and 670 nm, respectively), and reflect most of the greenlight

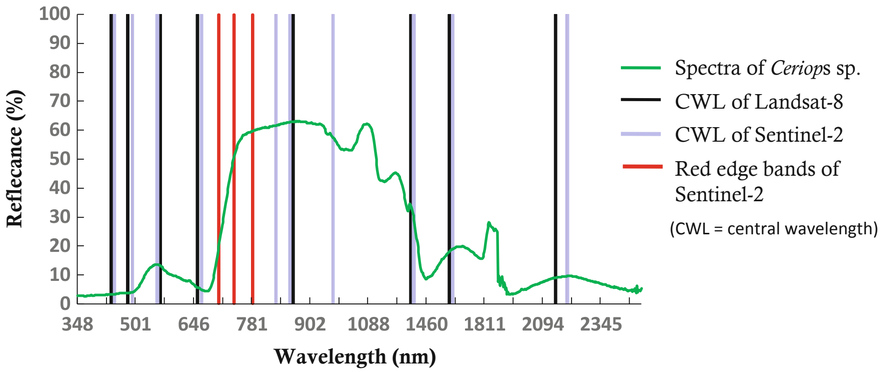

Fig. 4.1 Spectral profile of green vegetation and the locations of satellite wavebands

(centered around 533 nm), which enables leaves to appear green to the human eye (Knipling 1970). Greenlight is reflected back by the chlorophyll pigment within the chloroplasts in the palisade parenchyma cells. Blue light and red light are absorbed and used in photosynthesis by the chlorophyll pigments in the palisade cells. However, wavelengths in the near-infrared (NIR) region are mostly reflected and transmitted through the leaves, being scattered by the cell interfaces in the spongy mesophyll tissue (Jensen 2000). In healthy leaves, 40–60% of the NIR light is reflected, although at canopy level the situation is more complex because of a combination of responses such as additive reflectance, incidence angle, leaf orientation, shadow, and soil background reflectance. The absorption and reflectance in the shortwave infrared region (SWIR) are governed primarily by the leaf water content and partly by the leaf biochemicals including proteins, lignin, and cellulose. The reflectance increases in this spectral region as leaf moisture content decreases, and thus, the SWIR can be used to monitor plant water stress. Typical green vegetation reflectance and the locations of the satellite wavebands are given in Fig. 4.1.

4.3 Vegetation Indices

Developing various indices using contrasting response behavior of different bands toward leaf biochemicals is quite common to the remote sensing community. The linear indices enable highlighting the parameter of interest. Besides, the ratio indices considerably minimize the atmospheric effect. Large numbers of indices are available using different spectral regions of satellite wavebands as an indicator of plant biochemicals like pigments, moisture, lignin, cellulose, and biophysical indicators like leaf area index and canopy structure. Theoretically, vegetation indices (VIs) are mathematical expressions based on the reflectance measurements in two or more wavelengths across the optical spectrum to analyze specific characteristics of vegetation. VIs may be broadly categorized into three types: ratio indices [e.g., NDVI (Rouse et al. 1973)], orthogonal indices [e.g., thematic mapper (TM) tasseled cap transformation (Crist and Cicone 1984)], and others (e.g., Perry and Lautenschlager 1984). These indices also provide an effective classification for vegetation cover and can differentiate vegetation from other land cover classes. Several widely used VIs include Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Atmospherically Resistant Vegetation Index (ARVI), and simple ratio (SR). EVI was developed to improve the NDVI by optimizing the vegetation signal using the blue reflectance to correct for soil background signals and to reduce atmospheric influences (Huete et al. 1997). ARVI uses the reflectance in blue band to correct the red reflectance for atmospheric scattering. It is mostly useful in regions of high atmospheric aerosol content (Kaufman and Tanre 1992). SR is a simple, well-known index, and it is the ratio of the highest reflectance and absorption bands of chlorophyll (Sellers 1985). NDVI is a normalized ratio of red and NIR spectral reflectance and is one of the most popular indices, determined by the degree of absorption by chlorophyll in the red wavelengths. This index is proportional to leaf chlorophyll concentration, leaf structure, and green leaf density. The use of NDVI is sensitive to the green leaf area or green leaf biomass (Tucker 1979). In addition to the abovementioned canopy greenness indices, there are several other categories of VIs, particularly the ones for the study of vegetation canopy moisture content; e.g., Moisture Stress Index (MSI), Normalized Difference Infrared Index (NDII), Normalized Difference Water Index (NDWI), and Normalized Difference Moisture Index (NDMI) play pertinent roles in vegetation characterization. Table 4.1 enlists selected known VIs and their formulations that have been used by different authors in various mangrove studies across the world.

4.4 Vegetation Indices for Mangrove

Several investigators have proposed mangrove-specific vegetation indices to address the challenges in the identification of mangrove forests and their mapping (Table 4.2). One of which is the Mangrove Index (MI) proposed by Winarso et al. (2014). This index was first formulated using Landsat-8 Operational Land Imager (OLI) NIR and SWIR bands. The model was also tested on Landsat Enhanced Thematic Mapper (ETM+) data. The Mangrove Recognition Index (MRI) (Zhang and Tian 2013) was also developed for mapping mangrove forests using multi-temporal Landsat thematic mapper (TM) images at different tide levels and was found to be sensitive to the wetness and greenness. In the equation, the Green Vegetation Index (GVI) expresses the vegetation characteristics, while the Wetness Index (WI) provides information on canopy moisture content. GVI and WI are products of tasseled cap transformation, which is an orthogonal transformation of the remotely sensed data. Combine Mangrove Recognition Index (CMRI) was proposed by Gupta et al. (2018) that utilizes NDVI to express the presence of

Table 4.1 Existing and known VIs used in different mangrove studies

Vegetation index	Formulation	Formulation given by	Index used by	Purpose of the study
Simple ratio (SR)	NIR/R	Birth and McVey (1968) and Sellers (1985)	Jensen et al. (1991), Kovacs et al. (2009), Ibrahim (2009), Kongwongjan et al. (2012), Gupta et al. (2018) and Prananda et al. (2020)	• Estimation of percent mangrove canopy closure and used as a surrogate of mangrove density; • Comparative study of canopy greenness and vigor of different mangrove communities; • Differentiation of mangrove from non-mangrove areas; • Mangrove leaf area index modeling
Difference vegetation index (DVI)	NIR − R	Tucker (1979)	Ibrahim (2009)	• Comparative study of canopy greenness and vigor of different mangrove communities
Normalized difference vegetation index (NDVI)	(NIR − R)/(NIR + R)	Rouse et al. (1973)	Jensen et al. (1991), Kovacs et al. (2009), Ibrahim (2009), Kongwongjan et al. (2012), Umroh et al. (2016), Gupta et al. (2018), Prananda et al. (2020) and Aljahdali et al. (2021)	• Estimation of percent mangrove canopy closure and used as a surrogate of mangrove density; • Comparative study of canopy greenness and vigor of different mangrove communities; • Study of mangrove density; • Differentiation of mangrove from non-mangrove areas; • Mangrove leaf area index modeling; • Monitoring of canopy greenness of mangrove forests using time-series data

Enhanced vegetation index (EVI)	2.5 × ((NIR/R)/(NIR) + (6 × R) – (7 × B) + 1)	Huete et al. (1997, 2002)	Prananda et al. (2020) and Aljahdali et al. (2021)	• Mangrove leaf area index modeling; • Monitoring of canopy greenness of mangrove forests using time-series data
Green vegetation index (GVI)	GVI = − 0.2848B − 0.2435G − 0.5436R + 0.7243NIR + 0.0840SWIR1 − 0.1800SWIR2	Kauth and Thomas (1976) (used Landsat Thematic Mapper bands)	Jensen et al. (1991) [Systéme Pour I′ Observation de la Terre (SPOT) Multispectral bands]	• Estimation of percent mangrove canopy closure and used as a surrogate of mangrove density
Green atmospherically resistant vegetation index (GARI)	NIR − [G − γ(B − R)]NIR + [G − (B − ρR)] where γ is weighting coefficient of GARI	Gitelson et al. (1996)	Omar et al. (2019) and Prananda et al. (2020)	• Mangrove mapping and monitoring • Mangrove leaf area index modeling
Wide dynamic range vegetation index (WDRVI)	(α. NIR − R)(α. NIR + R) where α is weighting coefficient of WDRVI	Gitelson (2004)	Prananda et al. (2020)	• Mangrove leaf area index modeling
Infrared percentage vegetation index (IPVI)	NIR/(NIR + R)	Crippen (1990)	Ibrahim (2009)	• Comparative study of canopy greenness and vigor of different mangrove communities
Soil adjusted vegetation index (SAVI)	1.5 × (NIR − R)/(NIR + R + 0.5)	Huete (1988)	Ibrahim (2009), Gupta et al. (2018) and Kongwongjan et al. (2012)	• Comparative study of canopy greenness and vigor of different mangrove communities; • Differentiation of mangrove from non-mangrove areas
Modified soil adjusted vegetation index (MSAVI)	(NIR − R) × (1 + L)/(NIR + R + L) where $L = 1 - 2a \times$ NDVI×WDVI, a = soil line intercept	Qi et al. (1994)	Ibrahim (2009) and Aljahdali et al. (2021)	• Comparative study of canopy greenness and vigor of different mangrove communities; • Monitoring of canopy greenness of mangrove forests using time-series data

(continued)

Table 4.1 (continued)

Vegetation index	Formulation	Formulation given by	Index used by	Purpose of the study
Perpendicular vegetation index (PVI)	sin(a)NIR − cos (a)R where a = angle between soil line and NIR axis	Richardson and Wiegand (1987)	Jensen et al. (1991), Ibrahim (2009) and Kongwongjan et al. (2012)	• Estimation of percent mangrove canopy closure and used as a surrogate of mangrove density; • Comparative study of canopy greenness and vigor of different mangrove communities; • Differentiation of mangrove from non-mangrove areas
Triangular vegetation index (TVI)	0.5(120(NIR − G)) − 200(R − G)	Broge and Leblanc (2000)	Kongwongjan et al. (2012) and Zhu et al. (2017)	• Differentiation of mangrove from non-mangrove areas • Determination of mangrove vegetation status in terms of green LAI
Normalized difference wetland index (NDWI)	G − NIR/G + NIR	Gao (1996)	Gupta et al. (2018)	• Differentiation of mangrove from non-mangrove areas
Normalized difference infrared index	(ρ819 − ρ1649)/(ρ819 + ρ1649) where ρ is the reflectance of the particular band	Hardisky et al. (1983)	Tiwari and Kumar (2018)	• Study of mangrove canopy moisture status
Moisture stress index	ρ1599/ρ819 where ρ is the reflectance of the particular band	Hunt and Rock (1989)	Tiwari and Kumar (2018)	• Study of mangrove canopy moisture status
Normalized difference moisture index (NDMI)	(NIR − SWIR1)/(NIR + SWIR1) where SWIR1 wavelength range is 1.55–1.75 μm	Huete et al. (2002)	Aljahdali et al. (2021)	• Monitoring of moisture content of mangrove forests using time-series Landsat data

Normalized difference chlorophyll index (NDCI)	(R708 − R665)/(R708 + R665)	Mishra and Mishra (2012)	Caballero et al. (2020)	• Monitoring harmful algal blooms in complex coastal waters
Ratio of single-band reflectance to the sum of two-band reflectance (RSSI)	B8/(B2 + B5), B8*a*/(B2 + B4), B8/(B2 + B5), and B8/(B2 + B3) B = Sentinel - 2 bands	Tian et al. (2011)	Zhen et al. (2021)	• Estimating rice leaf nitrogen concentration

(*B* blue, *R* red, *G* green, *NIR* near-infrared, *SWIR* shortwave infrared)

Table 4.2 Mangrove indices for discriminating mangrove from non-mangroves

Vegetation index	Formulation	Satellite data used	Study area	Formulation given by
Mangrove index (MI)	MI = (NIR − SWIR/NIR × SWIR) × 10, 000	Landsat-8 OLI	Alas Purwo mangrove area, Banyuwangi East Java Province, Indonesia	Winarso et al. (2014)
Mangrove recognition index (MRI)	MRI = $\mid GVI_L - GVI_H \mid \times GVI_L \times (WI_L + WI_H)$ where *GVI* green vegetation index, *WI* wetness index, *L* at low tide, *H* at high tide	Landsat TM	Beilunhekou National Reserve Area, China	Zhang and Tian (2013)
Combine mangrove recognition index (CMRI)	CMRI = NDVI – NDWI where NDVI is the normalized difference vegetation index and NDWI is the normalized difference water index	Landsat-8 OLI	Mangrove forests of Bhitarkanika, Sundarbans, and Andaman Islands, India	Gupta et al. (2018)
Normalized difference wetland vegetation index (NDWVI)	NDWVI = (R2203 − R559)/(R2203 + R559) where *R* is the reflectance of the specific bands	EO1 Hyperion	Lothian Island, Sundarbans, India	Kumar et al. (2019)
Mangrove probability vegetation index (MPVI)	$\text{MPVI} - \frac{n\sum_{i=1}^{n} R_i r_i - \sum_{i=1}^{n} R_i \sum_{i=1}^{n} r_i}{\sqrt{n\sum_{i=1}^{n} R_i^2 - \left(\sum_{i=1}^{n} R\right)^2}\sqrt{n\sum_{i=1}^{n} r_i^2 - \left(\sum_{i=1}^{n} r_i\right)^2}}$ where n = total number of bands in the image, R_i is the reflectance value at band i for a pixel of the reflectance image, and r_i is the reflectance value at band i for candidate spectrum of mangrove forest	EO1 Hyperion	Lothian Island, Sundarbans, India	Kumar et al. (2019)

Mangrove forest index (MFI)	MFI = $((\rho\lambda1 - \rho B\lambda1) + (\rho\lambda2 - \rho B\lambda2) + (\rho\lambda3 - \rho B\lambda3) + (\rho\lambda4 - \rho B\lambda4))/4$ $\rho B\lambda i = \rho2190 + (\rho665 - \rho2190) \times (\rho2190 - \lambda i)/(\rho2190 - \rho665)$ where the $\rho\lambda$ is the reflectance of the band center of λ, and i ranged from 1 to 4; $\lambda1$, $\lambda2$, $\lambda3$, and $\lambda4$ represent the center wavelengths at 705, 740, 783, and 865 nm, respectively. $\rho B\lambda i$ is the baseline reflectance in λi. $\rho665$ and $\rho2190$ are the reflectance of band 4 s (centered at 665 nm) and 12 (centered at 2190 nm), respectively	Sentinel-2	Zhen Zhu harbour mangroves of Guangxi Province, China, and mangroves of Tonkin gulf	Jia et al. (2019)
Mangrove vegetation index (MVI)	MVI = (NIR − G)/(SWIR1 − G)	Sentinel-2	Five major mangrove sites in the Philippines and one in Japan	Baloloya et al. (2020)

G green, NIR near-infrared, SWIR shortwave infrared vegetation and Normalized Difference Water Index (NDWI) to obtain water information of mangroves without the need for tidal data. A Sentinel-2-based index called the Mangrove Forest Index (MFI) was proposed by Jia et al. (2019) that utilizes the reflectance of red-edge bands of Sentinel-2 imagery, which are sensitive to the submerged mangrove forests. The results showed that the submerged mangrove forests could be separated from the background water in the MFI output image. The study highlighted the ability of the NIR and red-edge bands in discriminating the vegetation from water. The Mangrove Probability Vegetation Index (MPVI) was proposed by Kumar et al. (2019) using bands derived from Earth Observing (EO)-1 Hyperion data. The MPVI identifies the Hyperion image pixels corresponding to mangroves by calculating their correlation coefficients with a candidate mangrove spectrum. Apart from the MPVI, the authors also proposed the Normalized Difference Wetland Vegetation Index (NDWVI) using Hyperion bands to discriminate mangrove from non-mangrove vegetation. Baloloya et al. (2020) proposed Mangrove Vegetation Index (MVI) for separating mangroves from other land use and land cover present in a single-tide Sentinel-2 image.

Table 4.3 highlights some important mangrove studies where different indices have been used to determine their health spatially. The research shows that the techniques are compatible with different satellite images and sensors, such as multispectral and hyperspectral, with moderate-to-high spatial resolutions. Moreover, these can be combined with other digital image classification techniques for improved performance.

4.5 Advantages and Limitations of VIs in Mangrove Studies

A particular VI is used for a specific purpose and should be carefully selected based on the application requirement with suitable validation tools and ground truth data. The major advantages of VIs in mangrove studies are as follows: (1) Calculation of simple VIs combining red and NIR bands can significantly improve the detection of green vegetation, which can be used to delineate mangrove areas from non-mangrove areas, (2) each VI has its specific expression of vegetation canopy that can be used to extract information on a specific biochemical parameter of mangroves such as LCC (Pastor-Guzman et al. 2015), nitrogen concentration (Fauzi et al. 2013), carotenoid concentration (Kumar et al. 2020), to name a few; further, these parameters can be analyzed and used for mangrove health assessment, and (3) VIs can be combined with other supervised and unsupervised classification outputs for better accuracy and validation purpose. There is ample scope for developing new VIs for mangrove ecosystems, which can be applied for determining the probability of finding true mangroves in a given area or that can separate true mangrove forests from patches of mangrove associates or from adjoining terrestrial vegetations using multispectral and hyperspectral remote sensing. While VIs are ubiquitous in remote sensing-based approach of vegetation health determination, there are some key limitations also, which include i) the choice of VIs need to be

Table 4.3 Vegetation index-based studies in mangrove health assessment

Objective	Sensor, image data type	Area	Algorithm/technique used	Reference
Leaf area index and mangrove condition	IKONOS, panchromatic and multispectral	Agua Brava lagoon mangroves, Mexican Pacific	Leaf area index modeling using NDVI	Kovacs et al. (2005)
Leaf area index and mangrove condition	QuickBird, panchromatic and multispectral	Agua Brava lagoon mangroves, Mexican Pacific	Leaf area index modeling using NDVI and SR	Kovacs et al. (2009)
Health assessment	Worldview 2 and RapidEye, panchromatic and multispectral	Lac Bay mangroves, Bonaire	NDVI, EVI, ARVI, red edge index, vegetation delineation tool, decision tree classifier	Davaasuren and Meesters (2012)
Health assessment	Landsat-8 OLI, multispectral	Alas Purwo mangrove area, Banyuwangi East Java Province, Indonesia	MI and NDVI	Winarso et al. (2014)
Estimation of foliar nitrogen concentration	HyMap, hyperspectral	Mahakam delta, East Kalimantan, Indonesia	Narrow-band vegetation indices and multivariate analyses	Fauzi et al. (2013)
Health assessment	Systéme pour I′ observation de la Terre–vegetation (SPOT-VGT), multispectral	Major mangrove ecosystems in India	NDVI time-series data, maximum value composite	Chellamani et al. (2014)
Health assessment	Hyperion Earth Observing-1 (EO1), hyperspectral	Thuraikkadu reserve forest area, Tamil Nadu, India	Soil adjusted vegetation indices (SAVI) as an additional parameter in support vector machine (SVM) and spectral angle mapper (SAM) classifications	Vidhya et al. (2014)
Leaf chlorophyll	Landsat-8OLI, multispectral	Yucatan peninsula, Mexico	Vegetation indices, leave one out cross–validation	Pastor-Guzman et al. (2015)
Leaf area index and vegetation status	Worldview 2, multispectral	Dawei Bay mangroves, China	20 different VIs derived from red edge and NIR bands in machine learning algorithms like artificial neural network regression (ANNR), support vector regression (SVR), and random forest regression (RFR)	Zhu et al. (2017)

(continued)

Table 4.3 (continued)

Objective	Sensor, image data type	Area	Algorithm/technique used	Reference
Health assessment	Landsat, multispectral	Mangroves in peninsular Malaysia	NDVI and SAVI	Razali et al. (2017)
Stress mapping of mangroves	Sentinel-2A, multispectral	Lothian wildlife sanctuary, Sundarbans, India	Discriminant normalized vegetation index (DNVI), NDVI, fuzzy classification technique	Manna and Raychaudhuri (2019)
Health assessment	Airborne visible infrared imaging spectrometer–new generation (AVIRIS-NG), sentinel-2A, hyperspectral, multispectral	Lothian wildlife sanctuary, Sundarbans, India	9 different narrowband VIs and DNVI, multi-criteria evaluation	Hati et al. (2021)
Health assessment	AVIRIS-NG, hyperspectral	Parts of Lothian Island, Sundarbans, India	Vogelmann red edge index 1 (VOG1), carotenoid reflectance index 1 (CRI1), modified chlorophyll absorption ratio index (MCARI), photochemical reflectance index (PRI) in decision tree classifier (rule-based)	Kumar et al. (2020)
Mangrove vegetation health index analysis	Sentinel-2A, multispectral	Segara Anakan, Kabupaten Cilacap, Indonesia	NDVI classification method	Akbar et al. (2020)
Study of mangrove stress	Landsat 5 TM, Landsat 7 ETM and Landsat-8 OLI, multispectral	Rabigh lagoon mangroves, Red Sea, Saudi Arabia	NDVI, EVI, MSAVI, and NDMI, time-series data analysis	Aljahdali et al. (2021)

made with caution by considering and analyzing the advantages and limitations of the existing and already known VIs, further combining or modifying them for application in a specific mangrove environment/habitat or study area, and ii) each VI has its expression of identifying vegetation, therefore, suited for specific purpose and application along with the sensor used.

4.6 Materials and Methods

4.6.1 Study Region

Sundarbans mangrove forest is extended over two neighboring countries, Bangladesh and India, and is bounded by 21°32′N to 22°13′ N latitude and 88°15′E to 89°53′ E longitude (Fig. 4.2). The mangrove forest area spans over South and North 24 Parganas districts of West Bengal State (India), and Khulna, Satkhira, and Bagerhat districts of Bangladesh.

The larger part of the Sundarbans (about 60%) is situated in Bangladesh and about 40% in India. Baleswar River of Bangladesh forms the eastern boundary, whereas Saptamukhi River of West Bengal (India) forms the western limit. The Indian part of the delta complex consists of 106 islands of which 54 are inhabited and 52 are forested islands, whereas in Bangladesh it consists of 31 islands. The entire Sundarbans, both Indian and Bangladesh, was inscribed as a World Heritage site by UNESCO in 1987 and 1997, respectively (https://whc.unesco.org). The landscape of the Sundarbans is characterized by a complex network of serpentine tidal waterways/ creeks, mudflats, and small islands of salt-tolerant mangrove forests.

The climate of the region is warm, tropical with high relative humidity between 70 and 88%, which is more or less uniform throughout the year. Winters are relatively cool and dry with average temperatures varying between 21 °C and 31 °C. The mean maximum temperature is 34 °C during June, and the mean

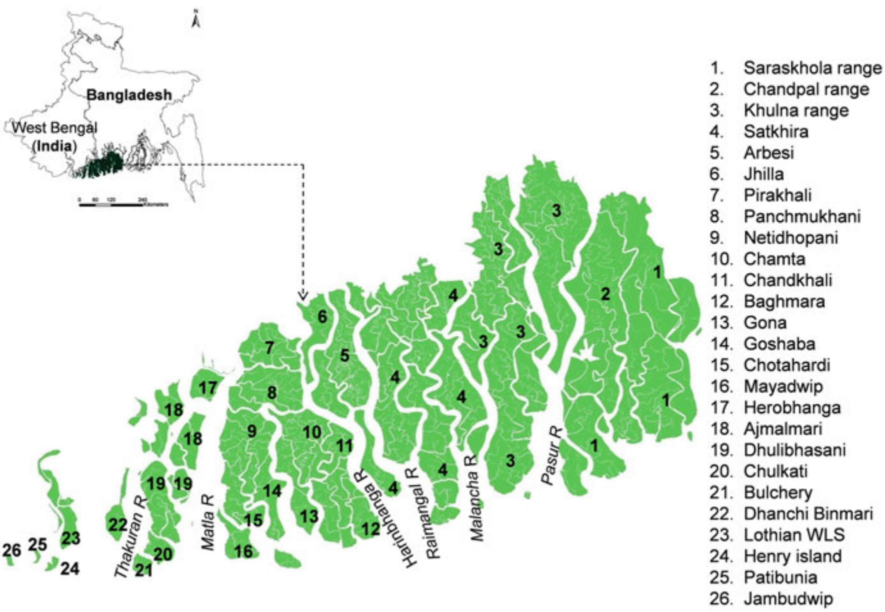

Fig. 4.2 Location of the study region with the names of major islands, Reserve Forests and Ranges

minimum temperature is 11 °C during January. The annual rainfall varies from 1640 to 2000 mm (Aziz and Paul 2015). The annual climate of Sundarbans can be classified into four seasons, viz. winter (December to February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October–November). The region experiences occasional rains throughout the year barring January and February (Choudhuri and Choudhury 1994). The monsoon period, which occurs between June and October, accounts for about 80% of the annual precipitation. Average annual rainfall of the region is 1920 mm. The winds are mostly from southwest in summer and north and northeast in winter and blow gently. During northwesters (March to May), however, wind speeds may rise up to 65 kmh^{-1}. Storms of very high intensity often occur early in the summer (in April and May) and late in the monsoon season (September to October, and sometimes November). These disturbances may produce winds with speeds exceeding 160 kmh^{-1} and may generate waves in the Bay of Bengal that crest as high as 6 meters before crashing over the shore with tremendous energy.

The landscape is characterized by a web of tidal water systems. The average tidal amplitude varies between 3.5 and 5 meters, with the highest amplitudes in July–August and the lowest in December–January. Of the eight major rivers that dominate the landscape only the Hugli, Ichamati-Raimangal, Arpangasia, Passur, and Baleswar carry freshwater flow of some significance. Being the moribund part of the lower delta plain of the GBM system, the Indian portion of Sundarban delta is experiencing both declining freshwater supplies and net erosion, as has been recorded since 1969 (Hazra et al. 2010).

The mangrove forests and the overall ecosystem in the Sundarbans are the ideal habitats for a large group of terrestrial, avian, and aquatic fauna, from protozoa to mammals. It contains the richest biodiversity among the inter-tidal forest in the world and is the only mangrove forest in the world, where the tiger (*Panthera tigris tigris* L.) resides. The reason for high faunal diversity is the fact that here the ocean and land come in contact of each other. The succession from ocean to land and to freshwater/brackish water through estuaries, change in water salinity from almost nil to high through grades of different concentration; newly formed islands with soft swampy mud to mature old islands with hard saline banks provides fascinating habitat opportunities to various organisms.

4.6.2 Flora of Sundarbans Delta

According to Champion and Seth (1968), the Sundarbans forest is tidal swamp forest, with sub-divisions of Mangrove type, saltwater type mixed forests, brackish type, and palm type. In general, the northern boundary and new depositions are characterized by Baen (*Avicennia marina*, *A. alba,* and *A. officinalis*) flanked by foreshore grassland of *Oryza coarctata* (Dhani grass). Baen is gradually replaced by

Genwa (*Excoecaria agallocha*) and then Goran (*Ceriops* sp.). The southern and eastern assemblages include Garjan (*Rhizophora* sp.), Kankra (*Bruguiera* sp.), and few patches of Sundari (*Heritiera fomes*). Hental (*Phoenix paludosa*) forest exists in relatively high land and compact soil. Dhundul (*Xylocarpus granatum*), Passur (*Xylocarpus mekongensis*), and *Nypa fruticans* (Golpata) palm swamps are extremely limited. There exist about 26 true mangrove species, 26 mangrove associates, and 29 back mangrove species. The major mangrove ecosystem zonation in Indian Sundarbans includes *Avicennia* dense, *Avicennia* moderately dense, *Avicennia* sparse, *Aegialitis–Excoecaria* dense, *Excoecaria agallocha* dense, *Phoenix paludosa* dense, mixed (*Avicennia–Excoecaria–Ceriops*) dense and mixed (*Ceriops–Excoecaria–Phoenix*) dense, mixed mangroves dense, fringe mangroves, saline blanks, marsh vegetation, sand/beach vegetation, and tidal mudflats (Ajai et al. 2012; ground data collection). Some of the field photographs are given in Fig. 4.3. The major mangrove communities found in Bangladesh include *Heritiera fomes*, *Heritiera fomes–Excoecaria agallocha, Heritiera fomes–Xylocarpus mekongensis*, *Heritiera fomes–Xylocarpus mekongensis–Bruguiera sexangula, E. agallocha*, *E. agallocha–Ceriops decandra*, *E. agallocha–H. fomes*, *E. agallocha–Phoenix paludosa*, *E. agallocha–Rhizophora–C. decandra*, *C. decandra–E. agallocha*, *C. decandra–P. paludosa*, *C. decandra–E. agallocha–H. fomes*, *Avicennia officinalis*, *A. officinalis–C. decandra–Aegiceras corniculatum*, *A. officinalis–A. corniculatum–C. decandra*, *A. officinalis–B. sexangula–C. decandra*, *P. paludosa–X. mekongensis–A. corniculatum*, *Sonneratia apetala*, *S. apetala–P. paludosa*, *X. mekongensis–B. sexangula,* and *X. mekongensis–B. sexangula–A. officinalis* (Nishat et al. 2019).

4.6.3 Satellite Data

The Copernicus Sentinel-2 mission comprises a constellation of two polar-orbiting satellites (S1A and S2B) placed in the same sun-synchronous orbit in the years of 2015 and 2017, respectively. Two identical satellites operate simultaneously, phased at 180° to each other, in a sun-synchronous orbit at a mean altitude of 786 km. The principal sensor onboard Sentinel-2 series is the multi-spectral instrument (MSI) that operates in 13 spectral bands spread over the visible/near-infrared (VNIR) and shortwave infrared (SWIR) region with a varying spatial resolution of 10–60 m (Table 4.4). The sensor contains four red-edge bands between 705 and 865 nm, which have proved successful for retrieving vegetation parameters. The main visible and near-infrared Sentinel-2A bands have a spatial resolution of 10 m, while its "red-edge" (red and near-infrared bands) and two shortwave infrared bands have a 20-m spatial resolution. The coastal/aerosol, water vapor, and cirrus bands have a spatial resolution of 60 m. The satellite has a revisit time of 5 days and with a pair of satellites in the same orbit. The swath width of the satellite is 290 km, while the radiometric resolution is 12 bit with a potential range of brightness levels between 0 and 4095.

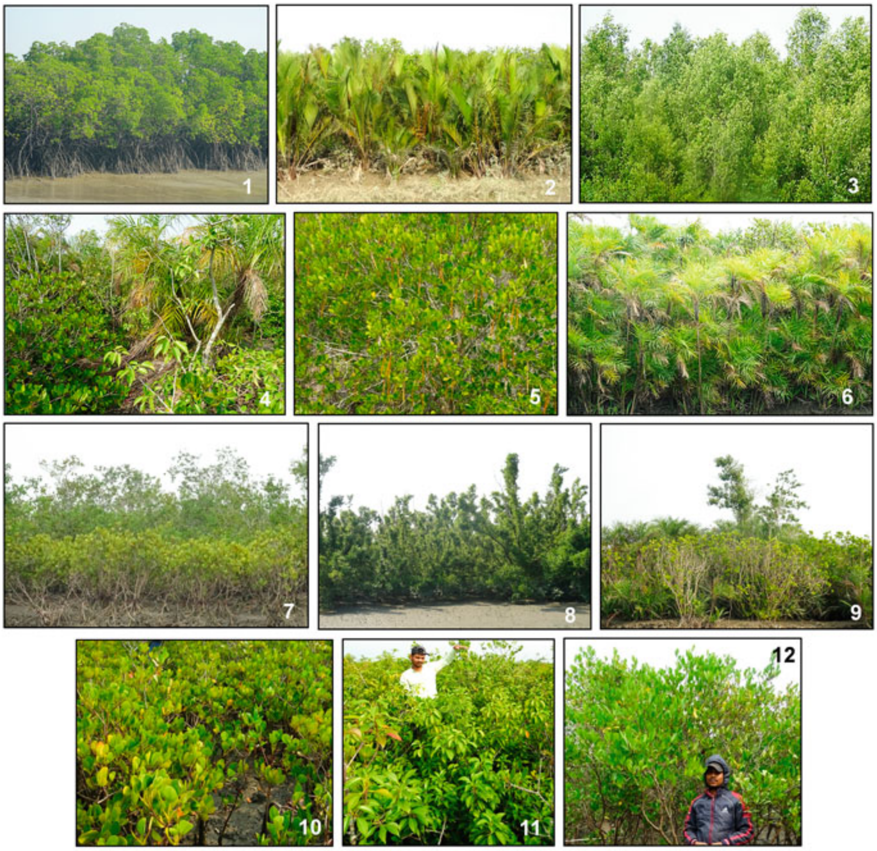

Fig. 4.3 Field photographs of Sundarbans mangroves. 1. *Rhizophora* thicket, Khatuajhuri, 2. *Nypa* thicket, Haribhanga, 3. *Avicennia* Dense, Netidhopani, 4. Mixed (*Ceriops-Excoecaria-Phoenix*) Dense, Patibunia, 5. *Ceriops* Dense, Panchmukhani, 6. *Phoenix* Dense, Pirakhali, 7. *Ceriops-Excoecaria* Dense, Pirakhali, 8. *Avicennia* Dense, Chulkati, 9. Mixed (*Ceriops-Excoecaria-Phoenix*) Dense, Ajmalmari, 10. *Ceriops-Aegialitis* Dense, Lot no. 126, 11. *Excoecaria* Dense, Bhubaneswari Char, 12. *Aegiceras* Dense, Jambudwip. Field photographs. 13. *Aegialitis* Sparse, Dhanchi-Binmari, 14. *Avicennia* Sparse, Lothian WLS, 15. Mangroves Sparse, Dobanki Camp, Panchmukhani, 16. *Avicennia* Sparse, Lothian WLS, 17. Degraded mangroves, Jambudwip, 18. Degraded *Avicennia*, Herobhanga, 19. Saline blank, Patibunia, 20. Marsh vegetation, Lothian WLS, 21. Tidal mudflat, Jambudwip

The principal objective of the Sentinel-2 mission is to monitor climate change, land use pattern, emergency management, and security. The improvements over its predecessors include the narrow bandwidth of MSI that could curtail the influence of atmospheric constituents such as water vapor, especially in the NIR region (760–900 nm). The aerosol correction of the captured image is facilitated by the inclusion of blue band at 443 nm (Band 1) in the MSI. On the other hand, the same blue band could be used to obtain vegetation indices.

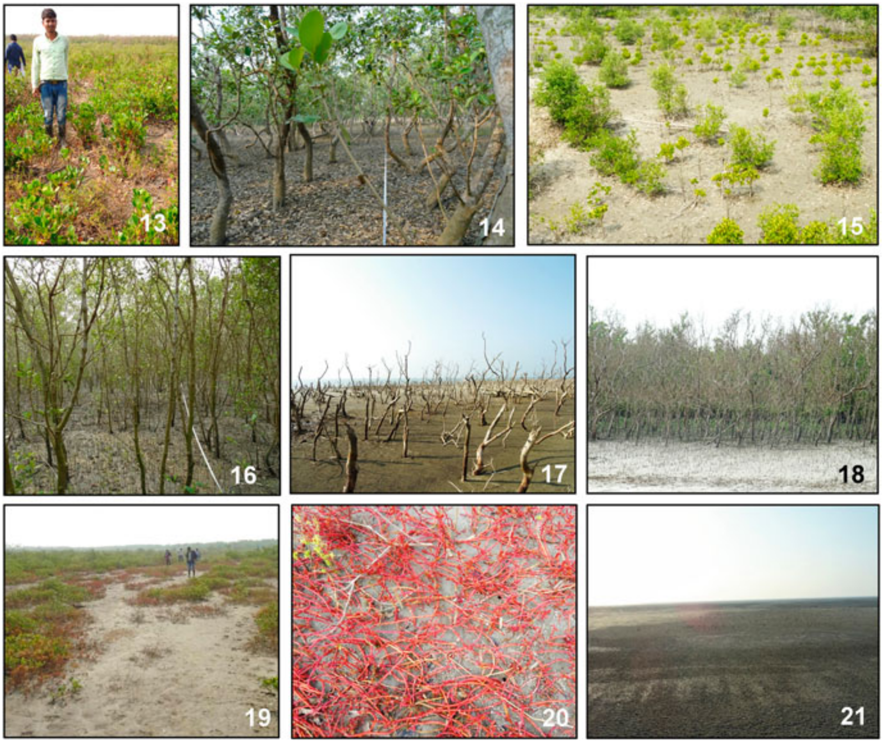

Fig. 4.3 (continued)

The short revisit time of Sentinel-2 proved to be advantageous for dynamic processes of land and the assessment of vegetation parameters (Sentinel 2 User handbook), viz. leaf area index (LAI), leaf chlorophyll content (LCC), and leaf cover (LC). Another important addition to MSI over Landsat series is the inclusion of four red-edge bands with 20 m resolution that are specifically designed to monitor vegetation and the vegetation moisture indices (Delegido et al. 2011; Xiao et al. 2020). The red-edge region lies between the red and near-infrared portion of the electromagnetic spectrum and is characterized by a sharp increase in the reflectance of green vegetation (Filella and Penuelas 1994). These bands are useful for monitoring green vegetation and more particularly the plant chlorophyll, nitrogen content, and crop type based on the sensitivity to different leaf and canopy structure (Kamenova and Dimitrov 2021). The vegetation indices derived from red-edge bands were found to be important for early detection of stress symptoms of forest stands and protection of forest resources (Dotzler et al. 2015).

In this study, altogether 177 Sentinel-2 (S-2) sub-scenes were examined for cloud contamination during 2019–20 and 2020–21, spanning between post-monsoon and early summer. The reason for choosing this window is primarily due to availability of cloud-free images. The entire Sundarbans is covered by three S-2 sub-scenes

Table 4.4 Wavelengths and bandwidths of Sentinel-2 (MSI)

Spatial resolution (m)	Band number	Sentinel-2A Central wavelength (nm)	Sentinel-2A Bandwidth (nm)	Sentinel-2B Central wavelength (nm)	Sentinel-2B Bandwidth (nm)
10	2	492.4	66	492.1	66
	3	559.8	36	559.0	36
	4	664.6	31	664.9	31
	8	832.8	106	832.9	106
20	5 (red edge)	704.1	15	703.8	16
	6 (red edge)	740.5	15	739.1	15
	7 (red edge)	782.8	20	779.7	20
	8a (red edge)	864.7	21	864.0	22
	11	1613.7	91	1610.4	94
	12	2202.4	175	2185.7	185
60	1	442.7	21	442.2	21
	9	945.1	20	943.2	21
	10	1373.5	31	1376.9	30

(T45-QXD, QXE, QYE). A total of 58 cloud-free, top of the atmosphere (TOA) reflectance scenes were downloaded from the EarthExplorer (https://earthexplorer.usgs.gov/), which is freely available in the public domain. These images correspond to Level 1C (L1C) radiometrically and geometrically corrected TOA products (ESA 2015). The calibrated TOA reflectance products are provided to the user community at their native spatial resolution, in 100 km × 100 km tile formats. The bottom-of-atmosphere corrected reflectance was produced after atmospheric correction using Sen2Cor module of Sentinel Application Platform (SNAP) software (Clevers and Gitelson 2013), which is a pre-requisite for chlorophyll estimation. As the number of cloud-free scenes of 2019–20 is very less in comparison with 2020–21, the observations and discussions are mainly based upon the S-2 data of November 2020 to April 2021.

4.6.4 Normalized Difference Vegetation Index (NDVI)

NDVI is one of the most popular vegetation indices introduced by Rouse et al. (1973). Both the broadband and narrow-band NDVI are operationally being used for vegetation health monitoring. It is given as follows:

$$\mathrm{NDVI} = (R_{\mathrm{nir}} - R_{\mathrm{r}})/(R_{\mathrm{nir}} + R_{\mathrm{r}}) \tag{4.1}$$

In this, the NIR band has been replaced by the red-edge band (8a) of S-2 (Zhang et al. 2018). Hence, the formula of the NDVI can be represented as follows:

$$\mathrm{NDVI} = (S_4 - S_{8\mathrm{a}})/(S_4 + S_{8\mathrm{a}}) \tag{4.2}$$

4.6.5 Normalized Difference Chlorophyll Index (NDCI)

NDCI is a band difference algorithm that uses the bands at 665 nm and 708 nm introduced by Caballero et al. (2020) specifically for the complex coastal waters. Two spectral features centered at the red (665 nm) and red-edge (708 nm) were used to develop NDCI. The formula of NDCI is given below:

$$\mathrm{NDCI} = (R_{664} - R_{704})/(R_{664} - R_{704}) = (S_4 - S_5)/(S_4 + S_5) \tag{4.3}$$

4.6.6 Normalized Difference Moisture Index (NDMI)

The NDMI is a normalized difference moisture index that uses NIR and SWIR bands to display moisture. The SWIR band reflects changes in both the vegetation water content and the spongy mesophyll structure in vegetation canopies, while the NIR reflectance is affected by leaf internal structure and leaf dry matter content but not by water content. The combination of the NIR with the SWIR removes variations induced by leaf internal structure and leaf dry matter content, improving the accuracy in retrieving the vegetation water content. The amount of water available in the internal leaf structure largely controls the spectral reflectance in the SWIR interval of the electromagnetic spectrum. SWIR reflectance is therefore negatively related to leaf water content. As the moisture content increases, the values become positive and higher. The equation of NDMI was introduced by Gao (1996).

$$\mathrm{NDMI} = (R_{864} - R_{1611})/(R_{864} + R_{1611}) = (S_{8a} - S_{11})/(S_{8a} + S_{11}) \tag{4.4}$$

where "*R*" refers to the spectral reflectance and "S" refers to Sentinel-2 bands.

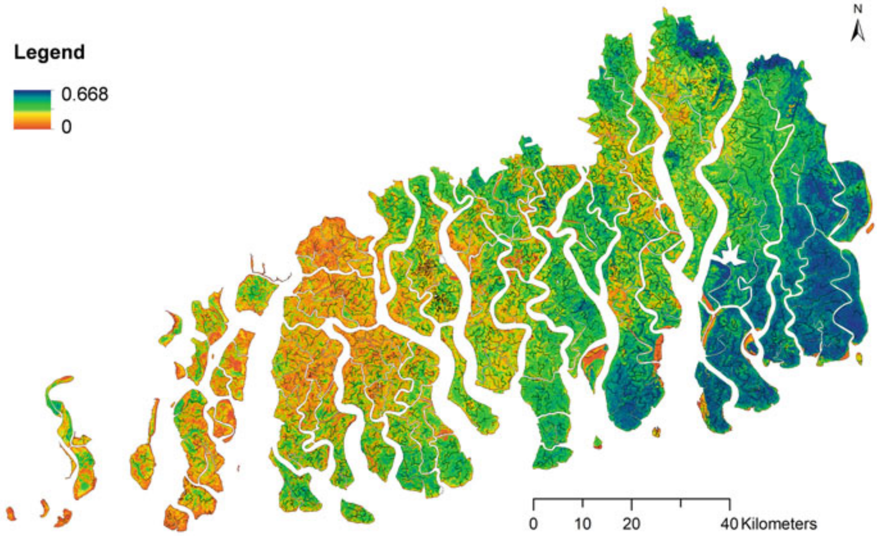

Fig. 4.4 Mean NDVI values of Sundarbans during the study period

4.6.7 Statistical Analyses of the Indices

The mean values of the indices from the spatial data were subjected to one-way analysis of variance (ANOVA) test to determine if there were any statistically significant differences between the group means. Further, post hoc analysis using Tukey's honestly significant difference (HSD) was computed for pairwise comparisons within the ANOVA data to determine between which of the pairs of means (if any of them) there is a significant difference.

4.7 Results and Discussion

4.7.1 Spatial Variability of Mean Values of Vegetation Indices

Mean NDVI and NDCI showed similar spatial patterns (Figs. 4.4 and 4.5). Very high values of VIs (>0.58 for NDVI and >0.4 for NDCI), dark blue areas Figs. A and B, mean the mangroves are healthy, and they were observed in the north of Khulna Range, almost entire Sarankhola, northern tip, and south of Chandpal Range. Similarly, high values were observed in the south of Khulna Range. Moderately high values of VIs (0.53–0.56 for NDVI and 0.37 to 0.39 for NDCI) were observed over west of Khulna, eastern half of Satkhira, and in the Indian Sundarbans region including Jhilla, Arbesi, Baghmara, Gona, Mayadwip, Chotahardi, Herobhanga, and

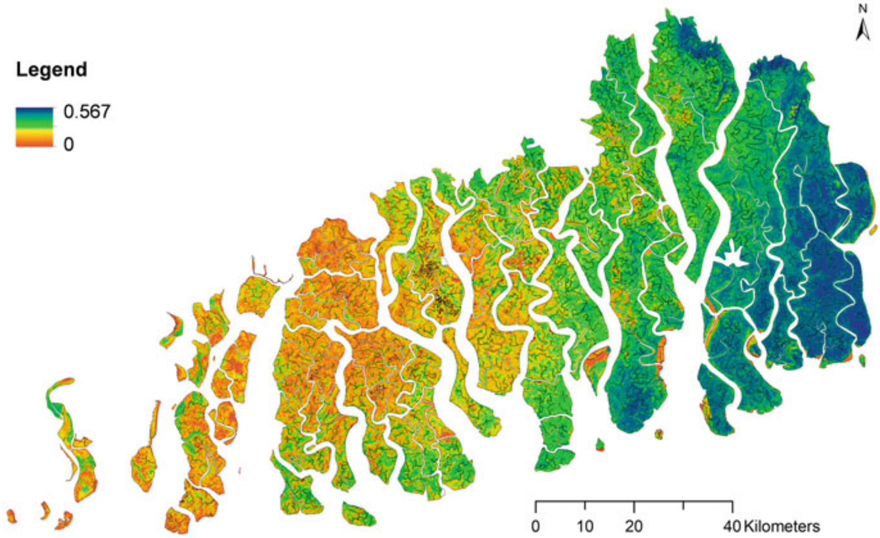

Fig. 4.5 Mean NDCI values of Sundarbans during the study period

parts of Ajmalmari, Dhulibhasani, Chulkati, Dhanchi-Binmari, and Lothian Wild Life Sanctuary (WLS). However, low to very low (<0.40 for NDVI and <0.30 for NDCI) VIs were noted in the northern portion of Indian Sundarbans, especially Pirakhali, Panchmukhani, northwest of Chamta, Netidhopani, Matla, Ajmalmari, Dhulibasani, Bulchery, Patibunia, Henry Island, and Jambudwip. In the Bangladesh Sundarbans, the regions that showed poor vegetation health includes most of the Chandpal and Khulna ranges (except the northern and southern tips) and west of Satkhira Range.

High values of the mean of NDVI and NDCI were prevalent in the regions dominated by *Heritiera*, *Heritiera–Excoecaria,* and *Excoecaria–Heritiera* communities in the Bangladesh side. Medium values of mean VIs were observed in the Bangladesh region where *Excoecaria*, *Excoecaria–Ceriops,* and *Ceriops* dominate. Similar values were observed in dense to moderately dense patches of *Avicennia*, *Aegialitis–Excoecaria*, *Excoecaria agallocha*, *Phoenix paludosa*, *Avicennia–Excoecaria–Ceriops,* and *Ceriops–Excoecaria–Phoenix* and mixed mangroves in the Indian side. Low mean values were mostly found in *Ceriops–Excoecaria* dominant regions in the Bangladesh side, as well as sparse and degraded mangroves, saline blanks, marsh vegetation, and mudflats in the Indian side.

In contrast to NDVI and NDCI, the canopy moisture (NDMI) showed a different picture wherein the Indian part of the Sundarbans region showed high values of NDMI (~0.52) in comparison with the Bangladesh portion of Sundarbans (Fig. 4.6). In general, there was a gradual increase in the canopy moisture from east to west of Sundarbans unlike the VIs for canopy greenness. Most of the Sarankhola, Chandpal, and Khulna ranges have shown very low canopy moisture to the tune of ~0.33,

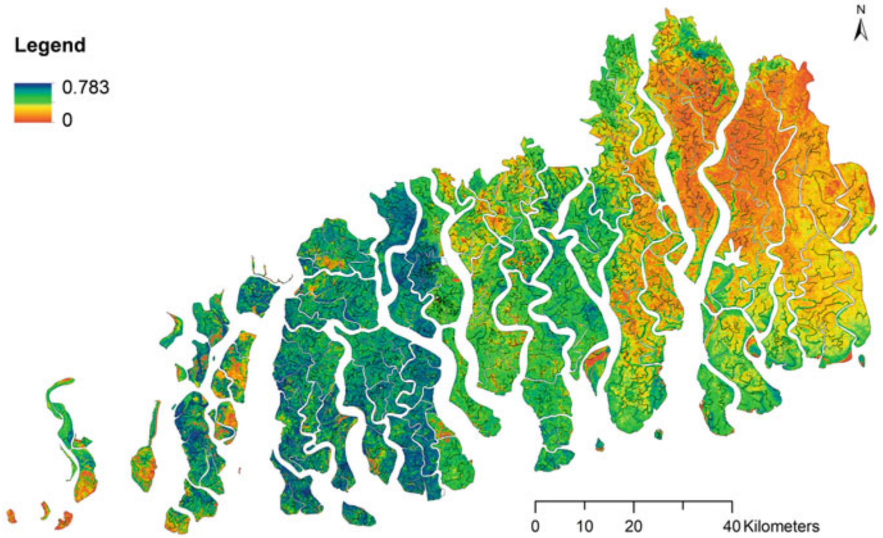

Fig. 4.6 Mean NDMI values of Sundarbans during the study period

which was continued up to the east of Khulna Range. Sporadic clusters of very low NDMI values (~0.2) were observed in the northern part of Satkhira, south of Pirakhali, north of Baghmara, Ajmalmari, Dhulibhasani, Dhanchi-Binmari, south of Lothian WLS, Henry Island, Patibunia, and Jambudwip.

The mangrove leaves are characterized by the presence of colorless water storage tissue, which is one of the anatomical adaptations to cope with the saline environment (Tomlinson 1986). Very low NDMI values were observed mostly over *Heritiera fomes* and *Heritiera fomes–Excoecaria agallocha* communities of Sarankhola, Chandpal, and Khulna ranges of Bangladesh Sundarbans. *Heritiera* is known to have low water storage tissue thickness (~0.037 mm) in the leaves (Das and Ghose 1996) and hence the reason for having low canopy moisture content. Contrary to this, locations dominated by *Xylocarpus mekongensis* communities in the Khulna and Satkhira ranges exhibited high NDMI values. This could be due to high water storage tissue thickness in the *Xylocarpus* leaves (~0.59 mm).

Satkhira Range that is dominated by *Ceriops decandra* assemblages showed moderate NDMI values (water storage tissue thickness in *C. decandra* leaves is ~0.097 mm). Further, the western side of Sundarbans (western Indian Sundarbans) has higher salinity and the eastern side of Sundarbans (east of Bangladesh Sundarbans) has lower salinity regime (Islam and Gnauck 2008), whereas the middle part of Sundarbans, covering some areas of India and more of Bangladesh, is polyhaline in nature (Karim 1988). Thus, in general, the soils in the Indian Sundarbans are more saline than the Bangladesh Sundarbans.

Higher NDMI values in the Indian side, dominated by *Avicennia–Excoecaria–Ceriops* and *Avicennia* communities, could be attributed to the more thickness of water storage tissue in the leaves and consequently more moisture content in the canopies as a result of increased salinity than the Bangladesh side. This finding is in agreement with one of the studies that was carried out for mangroves at Clyde River (Batemans Bay, New South Wales, Australia), wherein it was demonstrated that leaf water storage increased with salinity in *Avicennia marina* trees (Nguyen et al. 2017). Moreover, mangrove clusters with very low NDMI values in the Indian side were mostly the areas covered by saline blanks, sparse or degraded mangroves, and mudflats.

4.7.2 Statistical Analyses of the Indices

The purpose of one-way ANOVA was to examine whether the three indices represent different bio-optical indicators of vegetation health. Theoretically, NDCI is expected to present the canopy chlorophyll content, whereas NDVI8a and NDMI are representative of plant biophysical and moisture status, respectively. The summary of the spatial data for the different indices and the results of one-way ANOVA are given in Table 4.5. The value of F statistic obtained in the study was 44.575 and the results were significant at $p < 0.05$, thereby indicating that there were statistically significant differences in the mean values of the indices. Tukey's HSD test showed that there were significant differences in the means of NDCI and NDVI (Q statistic $= 11.92$, $p = 0.000$) and the means of NDCI and NDMI ($Q = 11.17$, $p = 0.000$), whereas there was insignificant difference in the means of NDVI and NDMI ($Q = 0.75$, $p = 0.858$). Hence, it can be concluded the Sentinel-2/MSI bands are

Table 4.5 Summary statistics and the results of one-way ANOVA

Summary of Data				
	Groups (various indices)			
	NDCI	NDVI8a	NDMI	Total
N	38	38	38	114
$\sum X$	11.354	17.064	16.71	45.128
Mean	0.2988	0.4491	0.4397	0.396
$\sum X^2$	3.5049	8.0513	7.5176	19.0739
Std. Dev.	0.0551	0.1025	0.0677	0.1035

ANOVA				
Sources of variability	Sum of the squares	Degrees of freedom	Mean square	F
Between groups	0.5387	2	0.2694	44.57562
Within groups	0.6708	111	0.006	
Total	1.2095	113		

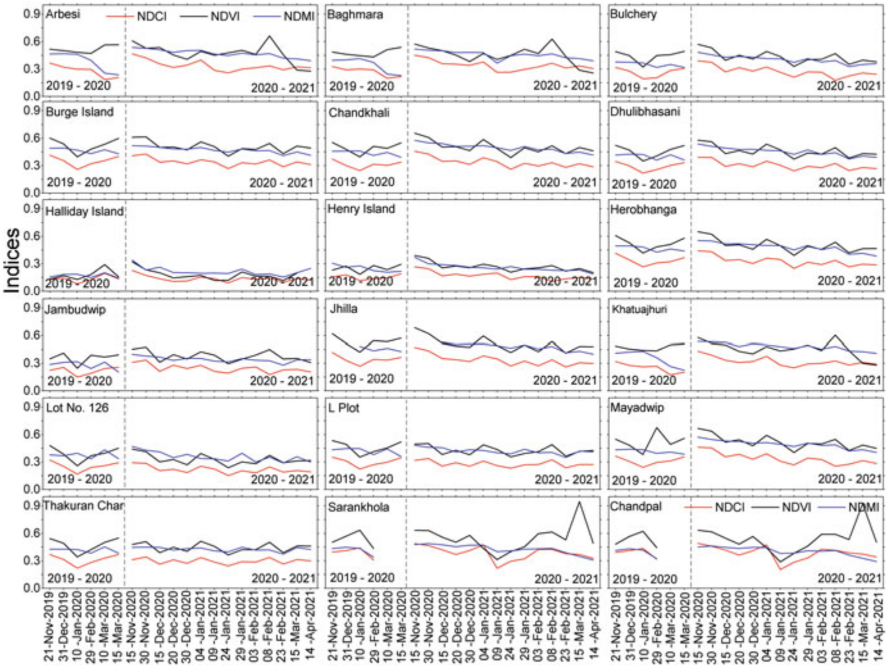

Fig. 4.7 Graphical representation of average NDVI, NDCI, and NDMI across 20 dates for 18 selected islands/reserve forests and ranges of Indian and Bangladesh Sundarbans

efficient for mapping mangrove health in terms of canopy chlorophyll, biophysical characteristics, and canopy moisture.

4.7.3 Temporal Profiles of the Indices

Based upon the cloud-free images of 2019–20 and 2020–21, the highest average NDVI value (0.95) was observed in Sarankhola Range, followed by Chandpal Range (0.93) on 15.03.21, whereas the lowest average NDVI value (−0.02) was recorded for Halliday Island on 14.04.21 as maximum portion of the island was inundated on that date of overpass (Fig. 4.7), and average NDVI value for Halliday Island on 14.04.21 has not been graphically represented in the figure. Considering all the studied dates, L plot and Chandpal Range exhibited the narrowest and the widest ranges of average NDVI values, respectively (Fig. 4.7). The maximum mean NDVI value was observed for Sarankhola Range (0.55), followed by that of Chandpal Range (0.54) (Fig. 4.8). In contrast, the minimum mean NDVI was estimated for Halliday Island (0.17), followed by that of Henry Island (0.26) (Fig. 4.8). Further, Halliday Island showed the highest mean standard deviation (SD), while Chandpal Range exhibited the lowest mean SD value (Fig. 4.8).

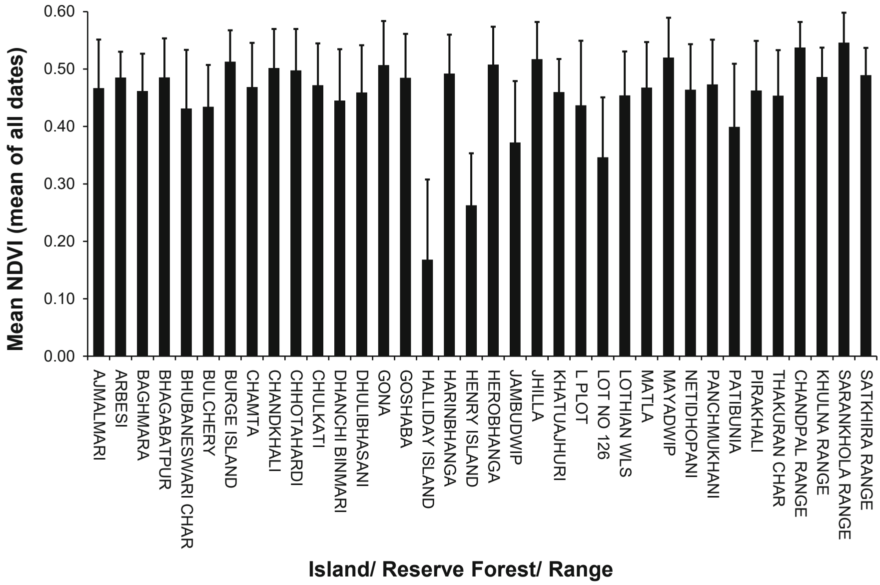

Fig. 4.8 Island/RF/range-wise graphical representation of mean NDVI (mean of all dates) with ± mean SD bars

The timings of occurrence highest average NDVI values (between November and April) are staggered with respect to the islands/RFs. Most of the islands/RFs (22 out of 36) showed the highest average NDVI values on 15.11.20. Two of the islands (L plot and Lot No. 126) showed maximum mean NDVI values on 21.11.19, whereas Bhubaneswari Char, Burge Island, and Jambudwip recorded highest values on 30.11.20. The timing of highest mean NDVI is delayed for the four islands of Bangladesh, viz. Chandpal, Khulna, Sarankhola, and Satkhira ranges, which are found on 15.03.21. In the Indian Sundarbans region, Arbesi, Baghmara, and Khatuajhuri exhibited the highest values on 08.02.21.

Similar to highest mean NDVI, the lowest mean NDVI also varies with time at different islands/RFs. Most of the islands/RFs (31 no) showed lowest mean NDVI during the month of January, especially in the second week of January. All the islands/ranges of Bangladesh Sundarbans show lowest mean NDVI on 09.01.21. The Indian Islands, viz. Jhilla and Mayadwip, showed lowest NDVI on 23.02.21 and 29.02.20, respectively (Fig. 4.7). The lowest mean NDVI is attained on 15.03.20 at Thakuran Char and on 14.04.21 at Arbesi, Baghmara, Halliday, and Khatuajhuri Islands. Therefore, to summarize, nearly 61% of the islands/RFs registered the highest average NDVI on 15.11.20 and about 52% of the islands/RFs showed the lowest average NDVI on 10.01.20.

The highest average NDCI value (0.49) was observed over both Chandpal and Sarankhola Ranges, followed by those in Arbesi (0.47), Jhilla (0.47), Mayadwip (0.46), and Chandkhali (0.46) on 15.11.20. The lowest average NDCI value (0.08)

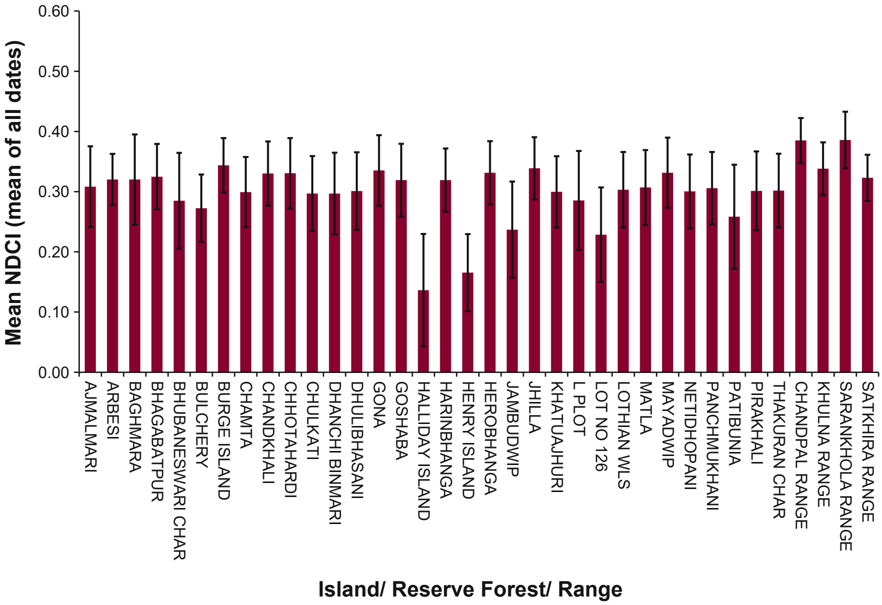

Fig. 4.9 Island/RF/Range-wise graphical representation of mean NDCI (mean of all dates) with ± mean of SD bars

was obtained for Halliday Island on 10.01.20, followed by Henry Island (0.11 on 08.02.21), Jambudwip (0.15 on 10.01.20) and Lot No. 126 (0.15 on 04.01.21) (Fig. 4.7).

Further, considering all the dates, L plot and Chandpal Range exhibited the narrowest and the widest ranges of average NDCI values, respectively (Fig. 4.7). The maximum mean NDCI (taking the mean of all the dates) was observed over Sarankhola Range (0.39), followed by Chandpal Range, whereas Halliday Island showed the minimum mean NDCI (0.14), followed by Henry Island (Fig. 4.9). Moreover, Halliday Island showed the highest mean SD, while Chandpal Range exhibited the lowest mean SD value (Fig. 4.9).

Similar to NDVI, most of the islands/RFs/ranges (29 out of 36) showed the highest average NDCI values as on 15.11.20. Two of the islands (L plot and Lot No. 126) showed maximum mean NDCI on 21.11.19. This is consistent with NDVI observations also. On 30.11.20, highest mean NDCI values were obtained by four of the islands, viz. Ajmalmari, Bhubaneswari Char, Burge Island, and Jambudwip. The highest NDCI value in Thakuran Char is attended during early summer on 15.03.20 (Fig. 4.7).

Most of the islands/RFs/Ranges (30 out of 36) registered the lowest mean NDCI values in the month of January. Out of 30, 20 islands/RFs/Ranges exhibit lowest NDCI on 10.01.20, four (of Bangladesh Sundarbans) on 09.01.21, and four (of Indian Sundarbans) on 24.01.21. The dip of NDCI is delayed (10.03.20) for three of

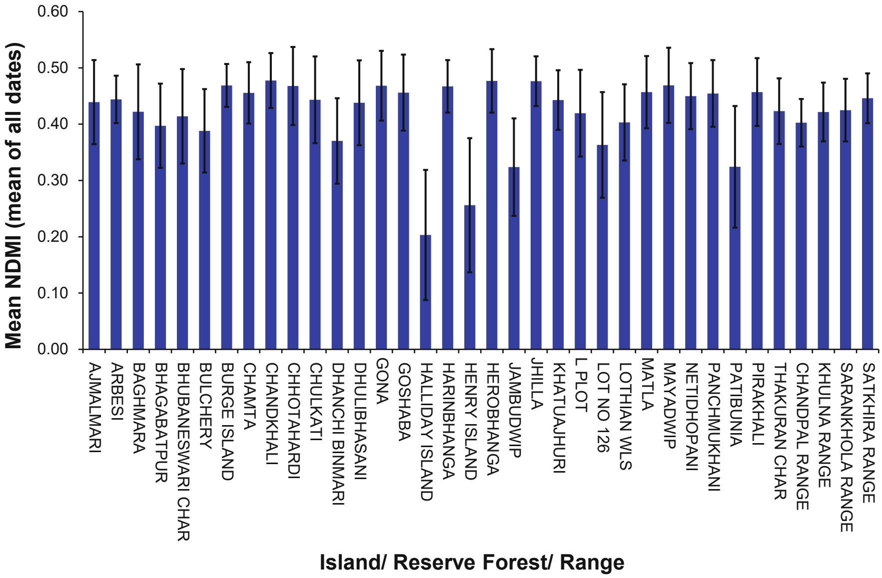

Fig. 4.10 Island/RF/range-wise graphical representation of mean NDMI (mean of all dates) with ± mean of SD bars

the islands/RFs, viz. Arbesi, Baghmara, and Khatuajhuri. Similar was the observation in case of NDVI also. The lowest mean values of NDCI were observed on 08.02.21 in Bulchery and Henry Islands and on 23.02.21 in Jhilla (Fig. 4.7). Hence, nearly 80% of the islands/RFs/ranges registered the highest average NDCI on 15.11.20 and about 61% of the islands showed the lowest average NDCI on 10.01.20.

The highest average NDMI value (0.58) was observed over Chandkhali, followed by those in Chhotahardi (0.57), Gona (0.57), Matla (0.57), Mayadwip (0.57), Goshaba (0.57), Jhilla (0.57), Haribhanga (0.57), and Chamta (0.57) on 15.11.20 (Fig. 4.7). The lowest average NDMI value (0.14) was observed over Halliday Island on 15.03.20, followed by Henry Island (0.19) on 14.04.21 (Fig. 4.7). Considering all the dates, Thakuran Char and Khatuajhuri recorded the narrowest and the widest ranges of average NDMI values, respectively (Fig. 4.7). The maximum mean NDMI (mean of all the dates) was observed over Chandkhali (0.48), whereas Halliday Island showed the lowest mean NDMI (0.2), followed by Henry Island (Fig. 4.10). Henry Island showed the highest mean SD, while Burge Island exhibited the lowest mean SD (Fig. 4.10).

Thirty-one islands/RFs of Indian Sundarbans showed highest average NDMI on 15.11.20, whereas in the four ranges of Bangladesh Sundarbans the highest values were attained on 30.11.20. Interestingly, Thakuran Char shows the highest values on 10.03.20 (Fig. 4.7). The lowest mean NDMI values are observed between 23.02.21 and 14.04.21. About 64% of the islands/RFs/ranges exhibited lowest NDMI values on 15.03.20, whereas 14% each on 23.02.21 (Bhubaneswari Char, Burge Island, L plot, Lot No. 126, and Thakuran Char) and 14.04.21 (Henry Island, Herobhanga, Jhilla, Chandpal, and Sarankhola Ranges). Three of the islands/ranges, viz. Dhulibhasani, Khulna, and Satkhira ranges, showed lowest mean NDMI values on 29.02.20 (Fig. 4.7). Thus, it can be stated that nearly 86% of the islands/RFs/ranges registered highest average NDMI on 15.11.20, while about 63% of the islands showed lowest average NDMI on 15.03.20. For most of the islands/RFs/ranges, the trend or the pattern of increase or decrease in average values with dates was found to be broadly similar for NDVI and NDCI, excepting for Henry Island and Herobhanga (Fig. 4.7).

In general, there is a decreasing trend in all the vegetation indices between November and April in case of Indian region of Sundarbans. There is sharp dip in the fourth week of January in the NDCI and NDVI in all the islands of Indian Sundarbans; however, in Bangladesh region both the indices showed significant decrease in the second week of January itself. Moreover, the dip got extended till the end of January, especially in case of Satkhira Range. Overall, VI values in Halliday and Henry islands were very low, which could be possibly due to persistent inundation of the Halliday Island and the presence of aquaculture ponds and saline blanks in Halliday and Henry Islands, respectively.

In this study, three types of VIs for canopy pigment content and one for canopy moisture were utilized to understand the health of mangrove vegetation of Sundarbans. Both the NDVI (using red-edge band of S-2) and NDCI are first time being used for vegetation health analysis over Sundarbans region. This study makes an attempt to provide a time-series product on spatial distribution of proximal indicator of leaf chlorophyll content at landscape level. Due to lack of field-based observations, especially in the Bangladesh region of Sundarbans, it was not possible to validate the findings in the ground. Moreover, being located in the tropical region it is difficult to obtain optical satellite data of good quality during the summer monsoon. Scalability is another issue wherein field-level information on leaf chlorophyll cannot be inverted at canopy level, which is much more complicated due to an intermix of soil, dry/green vegetation, and shadow within the footprint of sensor's instantaneous field of view. In this study, S-2 data were able to accurately detect the spatial variability in the VIs and canopy moisture due to the finer pixel size of S-2 data. Hence, S-2 data can be operationally used for monitoring the mangrove health.

4.8 Conclusions

The twin Sentinel-2A/B (S2) satellites of the European Union's Copernicus earth observation program, carrying the MSI sensor, have opened a new vista for multiple applications including vegetation health. The sensor containing three notable wavebands in the red-edge portion is a promising tool for retrieving canopy chlorophyll content at a regional scale. The S-2 multi-temporal data during post-monsoon to early summer reveal the micro-level variability in canopy chlorophyll and moisture status of integrated Sundarbans of India and Bangladesh. The spatiotemporal maps are extremely useful for dynamic monitoring of mangrove health and especially after natural calamities for damage assessment. Three red-edge bands location at 704, 740, and 783 nm with high spatial resolution (10 m) have proven its utility for mangrove health mapping. Vegetation indices employing these red-edge bands can provide additional information on leaf and canopy structure as well as early detection of stress. The multi-temporal data of November 2020–April 2021 reveal significant difference in the canopy chlorophyll wherein in the eastern part of the Sundarbans, viz. the Sarankhola, south of Chandpal and Khulna Range and the northern tip of Khulna and Chandpal Ranges exhibits good health, but the rest of the Sundarbans mostly have medium-to-poor chlorophyll content. In the Indian region, the islands/RFs that have medium values of VIs include south of Baghmara, Gona, Mayadwip, Chhotahardi, Herobhanga, Jhilla, and Arbesi. In general, the highest values of the VIs are attained during November and lowest during February–March. The canopy moisture, however, exhibited a contrasting feature while comparing with the pigment indices. The values of NDMI are low in the eastern part of Sundarbans including most of Sarankhola, Chandpal, and entire eastern part of Khulna Range except the eastern portion. In contrast, the canopy moisture appears to be more in the western half of Sundarbans falling in the Indian region. This observation is interesting and needs further investigation at the field level to understand the actual reasons.

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Chapter 5
Ethnobotany of Mangroves: A Review

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Abstract This review deals with 72 species of mangrove plants covering 42 genera and 29 families used by local communities. The primary use is domestic consumption for fuelwood and used in construction, poles, fences, shelters, thatch, and boat repair. Mangroves are also an important resource for a wide range of non-wood forest products such as honey, bark for tannin as a dye, foliage for fodder for camels and cattle, edible products, sugar, alcohol and vinegar, and many medicinal properties used for treating a variety of diseases such as snakebite, skin diseases, kidney disorders, rheumatism, smallpox, ulcers, boils, abscesses, stomach disorders, asthma, leprosy, epilepsy, diarrhea, nausea, vomiting, typhoid, hepatitis, diabetes, external bleeding, sprains, and swellings. Mangrove forests are getting degraded due to high anthropogenic activities leading to disappearance of forests. Conservation of vegetation and natural regeneration should be given top priority. Steps should be taken for in situ and ex situ conservation of economically useful plants of existing mangrove vegetation.

Keywords Ethnobotany · Mangroves · Medicinal properties · *Rhizophora* · *Avicennia*

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5.1 Introduction

Mangrove is an ecological term referring to a taxonomically diverse assemblage of trees and shrubs that form the dominant plant communities in tidal, saline wetlands along sheltered tropical and subtropical coasts (MAP 2002). The word mangrove is a combination of a Portuguese word “Mangue” for an individual tree, and groove is the English word for a group of trees. Mangroves are estuarine and developed in lagoons and in the fringing or barrier reefs of corals or islands. Mangroves are usually found only in tropical climates, as they need consistently warm conditions for development and survival. They are largely confined to the regions between 30° north and south of the equator (Bandaranayake 2002). Mangroves are found in 123 countries across the globe (Spalding et al. 2010). The total area covered by mangrove trees in the world was estimated to be 137,760 km^2 in 2000 (Giri et al. 2011), and currently mangroves covered about 152,000 km^2 (Yeo 2014). Approximately 75% of mangroves are found in 15 countries but only 6.9% are protected (Thomas et al. 2017). The mangroves of the world can be mainly divided into eastern and western groups. Eastern group covers the region from west and central pacific to the southern end of Africa. Western group covers the regions American and African coasts of Atlantic Ocean, the Caribbean Sea, and Gulf of Mexico or the west coast of Africa and coastal regions of North and South America.

Mangrove estuarine environments are strongly dynamic in nature. Numerous channels and creeks alternatively wash these very special wetlands with fresh water and tidal saline water twice a day. The mangroves have to encounter high salinity, tidal extremes, heavy winds, high temperatures, and anerobic soil substrates. Mangrove species are classified as true mangroves and mangrove associates. True mangroves differ from mangrove associates physiologically and ecologically in their ability to survive in the mangrove environment (Wang et al. 2011). In total, there are about 84 mangrove plant species belonging to 24 genera and 16 families distributed throughout the world, out of which only 70 species are reported as true mangroves and the rest 14 as mangrove associates (Jun et al. 2008). Mangroves have developed morphological, physiological, and/or reproductive strategies adapted to the harsh saline, waterlogged, and anerobic environmental conditions (Tomlinson 1986; Duke 2006; Hogarth 2007; Spalding et al. 2010; ITTO 2012). The strategies include coping with salinity through ultra-filtration and salt glands; aerating roots with lenticels to facilitate gaseous exchange; vivipary and cryptovivipary to enable rapid establishment and early growth of seedlings; and buoyant propagules to facilitate water dispersal.

Mangrove forest is a vegetation community formed by a variety of salt-tolerant species growing in the intertidal areas and estuary mouths between land and sea. Mangrove forests are one of the most productive wetlands on the earth (Alongi 1996). They provide critical habitat for a diverse marine and terrestrial flora and fauna. Mangrove forests not only play an essential role as the source of food for marine organisms but the evergreen floral community are also a good source of food and medicinal use for humans, as they are well adjusted to water stress and with high nutrient potential (Lim et al. 2006; Carvalho 2007). Traditionally, local communities in mangrove ecosystems collect fuelwood, fodder, medicine from plant parts and harvest fish and other natural resources (Bandaranayake 1998; Dahdouh-Guebas et al. 2000). Mangroves are also considered as ecologically important in protecting adjacent land from sea waves and storm erosion (Banijbatan 1957). Mangroves are important ecosystems that provide a wide range of goods and services to human communities living in coastal areas. The array of benefits derived from mangroves includes wood and non-wood forest products, fisheries, recreation, ecotourism, bio-filtration, coastal protection, and carbon storage and sequestration (Saenger et al. 1983; Ewel et al. 1998; Hogarth 2007; Walters et al. 2008; Spalding et al. 2010). Yet, these unique coastal tropical forests are among the most threatened habitats in the world. Understanding the uses and value of the ethnobotany of the mangroves can help in their protection and conservation management.

5.2 Mangrove Uses

The ethnobotany of important mangrove plant species is arranged in alphabetical order with botanical name followed by family, vernacular name, and its uses in Table 5.1. Mangroves are used as timber; fuelwood; raw materials for the wood-based industry and leather tanning industries; and raw materials for indigenous medicine and edible products.

5.2.1 Timber and Fuelwood

There are relatively few studies on the human uses of mangroves but publications on mangroves from around the world in Africa—Kenya (Dahdouh-Guebas et al. 2000; Obade 2000; Obade et al. 2004) and Tanzania (Kajia 2000); Asia—Vietnam (Stolk 2000) and Philippines (Primavera 2000; Walters 2005); and Americas—Mexico (Hernández-Cornejo et al. 2005) all report that construction and fuelwood are the primary uses of mangrove species. In West Bengal, India, *Bruguiera gymnorrhiza* and *Heritiera littoralis* have been reported as particularly valuable timber (Pernetta 1993). In Kenya, *Rhizophora* is favored for house construction because of their ability to grow long and straight (Dahdouh-Guebas et al. 2000). *Rhizophora, Bruguiera,* and *Ceriops* are characterized by their heavy hardwood and tannin-rich bark. As such, they are widely valued for construction, fuelwood, and tannin extraction (Ewel et al. 1998). Coastal communities in many tropical countries continue to rely heavily on mangrove wood for domestic consumption for fuel, construction, poles, fences, shelters, and boat repair (Dahdouh-Guebas et al. 2006). There are also well-established commercial markets for mangrove fuelwood and charcoal. Mangrove wood is also an industrial source of pulp for manufacturing rayon, cellophane, and paper.

Table 5.1 Ethnobotanical uses of important mangrove plant species

No.	Botanical name/Family/Vernacular name	Uses
1	*Acanthus ebracteatus* Vahl Acanthaceae	Leaves used as herbal tea in Thailand (Baba et al. 2013)
2	*Acanthus ilicifolius* L. Acanthaceae/*Aalchi Horgoja, Kazimulli Harakancha, Hurgoia Hargoja* (Fig. 5.1)	Root tied to white thread and worn by expectant mothers is believed to hasten childbirth. Leaf paste placed on forehead in acute headache and for rheumatism. Fruit pulp is used as blood purifier (Tribedi et al. 1993) Whole-plant extract and paste are used for skin diseases, smallpox, health promotion, detoxification, and ulcer (Ravindran et al. 2005) Crushed fruits are used for snakebite. Whole plant is boiled in water and the patient drinks half a glass each time until the signs and symptoms of the kidney stone disappear Aphrodisiac, asthma, diabetes, rheumatism, snakebite (Pattanaik et al. 2008) Fruit pulp used as blood purifier and dressing for boils and snakebite. Leaf is used for rheumatism. Leaf juice is applied as hair preserver (Rao and Murty 2014) Leaves are traditionally used for treating tiger bites. Roots are boiled and extract used to treat asthma, paralysis, leucorrhea, and debility (Chowdhury et al. 2014) Roots, tender shoots, and leaves are used in snakebite, asthma, cough, nerve tonic, wounds and boils, aphrodisiac, diabetes, rheumatism (Sathe et al. 2014) Decoction of bark with equal amount of honey and pinch of cumin powder is given for dyspepsia. Paste of leaves is applied for joint pains in case of snakebite, skin diseases, and kidney disorders (Soman 2014) Leaves and fruits are used for skin diseases, kidney stone, smallpox, ulcer, and snake poison (Bello and Aiyeloja 2015) Folklore claims this plant as aphrodisiac, blood purifier, diuretic, for treatment of asthma, diabetes, dyspepsia, hepatitis, leprosy, neuralgia, paralysis, ringworm, rheumatism, skin diseases, snakebite, stomach pains, leucorrhea, and leukemia, in Thai traditional medicine. It is used as a purgative and as an anti-inflammatory Leaves are dispensed with pepper as tonic pills for longevity (aphrodisiac). It is also employed as an emollient fomentation for rheumatism and neuralgia. It is widely believed among mangrove dwellers that chewing the leaves will

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		protect against snakebite. Tea brewed from the leaves relieves pain and purifies blood. The root boiled in milk is largely used in leucorrhea and general debility A decoction of the plant with sugar candy and cumin is used for dyspepsia. Leaves are bruised and soaked in water for external application and are also used as an expectorant. It is also considered to be a diuretic, and it is used as a remedy for dropsy and bilious swellings (Saranya et al. 2015) Crushed leaves make a good blood purifier and dressing for boils and snakebites (Goutam and Abhijit 2017) Leaves are used for asthma, diabetes, rheumatism (Khomne et al. 2018) Treats paralysis, asthma, diuretic, dyspepsia, hepatitis, leprosy, rheumatic pains, analgesic, anti-inflammatory, and leishmanicidal (Vinoth et al. 2019) Whole plant is used for aphrodisiac, rheumatism, relief for asthma, diabetes, diuretic, dyspepsia, leprosy, hepatitis, blood purifier, cure for cold, gangrenous wounds, skin allergies, snakebites in Bangladesh; analgesic, wound healing effect in West Bengal; and leaf is used for pain relief. Leaf is used for rheumatism neuralgia, snakebite, paralysis, and asthma in Sundarbans; fruit is used for snakebite and whole plant is used for detoxification, kidney stone, smallpox, skin diseases, ulcers in Pichavaram, India; plant is used for rheumatism, asthma, paralysis, psoriasis, leucorrhea in South Thailand; leaf is used as blood purifier, snakebite, and rheumatism in Thailand (Sadeer et al. 2019)
3	*Acanthus volubilis* L. Acanthaceae/*Lota, Horgoja, Hurgtxha, Lata horgoja*	Leaf paste is applied on boils, cuts, and wounds (Tribedi et al. 1993) Leaves are dried and taken as a remedy for stomach ulcers (Chowdhury et al. 2014) Leaf extract is used to cure bone fractures (Goutam and Abhijit 2017)
4	*Acrostichum aureum* L. Pteridaceae/*Hudo Kharkhari*	Applied on wounds and boils and to treat rheumatism; dried fronds are used for thatching (Pattanaik et al. 2008) Frond stalks used as vegetables in Malaysia and Sri Lanka (Baba et al. 2013) Rhizome paste is used to treat boils and carbuncles (Chowdhury et al. 2014)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		Rhizome and leaves stop bleeding, wounds, and boils (Bello and Aiyeloja 2015) Rhizome and leaves used to stop bleeding; leaves and bark are used for wounds and boils (Khomne et al. 2018) Whole plant is used for astringent, hemorrhage, and worm remedy in Kerala, India (Sadeer et al. 2019)
5	*Acrostichum speciosum* Willd. Pteridaceae	Rhizome and leaves used for boils and wounds (Bello and Aiyeloja 2015) Bark and leaves used for boils and wounds (Khomne et al. 2018)
6	*Aegialitis rotundifolia* Roxb. Plumbaginaceae/*Banarua, Satutt*	Whole plant is used for family planning. Paste of the plant is applied to get relief from rheumatic pain (Tribedi et al. 1993) The latex is used as medication for toothache Fruits are made into chutney and taken once a day for 15 days to increase appetite (Dash et al. 2007) Timber, wood for construction, and honey collection (Pattanaik et al. 2008) Leaf is used for pain relief, inflammation, antiache agent, and antidote for insect bites, pyrexia in Bangladesh (Sadeer et al. 2019)
7	*Aegiceras corniculatum* (L.) Blanco. Myrsinaceae/*Guggilam, Dudumara, Kharsi*	Used for asthma and diabetes; leaves for fish poison; wood for fishing, furniture, and boats (Pattanaik et al. 2008)
8	*Aglaia cucullata* Pellegrin Meliaceae/*Ooanra*	Wood used for construction (Pattanaik et al. 2008)
9	*Alstonia spatulata* Blume Apocynaceae	Wood is used for preparation of masks which is light, soft, and easy to carve (Baba et al. 2013)
10	*Alternanthera paronychioides* A. St. Hil. Amaranthaceae/*Julsachi*	Plant paste is applied on burns. The plants are also used as fodder for enhancing yield of milk (Tribedi et al. 1993)
11	*Annona senegalensis* Pers. Annonaceae/A*gnouglwetin*	Leaves are used in human infertility (Dossou-Yovo et al. 2017)
12	*Atalantia correa* Roem. Rutaceae/*Bon Lebu*	Oil from fruit is used for rheumatism (Chowdhury et al. 2014)
13	*Avicennia africana* L. Avicenniaceae/*Akpontin*	Bark or stem used for antitumor, antiulcer, thrush, gangrenous wounds, lice, mange, ringworms, and skin parasites (Thatoi et al. 2016) Roots used for malaria (Dossou-Yovo et al. 2017)
14	*Avicennia alba* Blume Avicenniaceae/*Vilalamada, Vilvamada Kandal, Kala bani*	Resinous substances used for birth control (Ravindran et al. 2005) Plant is used for fuelwood (Dahdouh-Guebas et al. 2006)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
	Gundumada, Samaekhao, Pearabain	Bark paste is externally applied over fresh wounds to arrest bleeding (Dash et al. 2007) Antifertility, skin diseases, ulcers, contraceptive, fodder, and fuelwood (Pattanaik et al. 2008) Heartwood decoction is given orally as blood tonic (Neamsuvan et al. 2012) Stem extract and resinous substances used for birth control (Madhu 2013) Bark is used for skin diseases, fruit for fish food, resinous exudates for birth control, and seed ointment for smallpox (Rao and Murty 2014) Young leaves used for cuts and wounds (Bello and Aiyeloja 2015) Bark and stem used for contraceptive, antifertility, paralysis, scabies, rheumatism, aphrodisiac, asthma, skin disease, sexual disorders, snake bite, analgesic and antiulcer, and boils (Thatoi et al. 2016) Seed used for smallpox ulcerations (Goutam and Abhijit 2017) Leaves used for rheumatism, smallpox, and ulcers (Khomne et al. 2018)
15	*Avicennia germinans* L. Avicenniaceae	Wood used for cooking food like yam, plantain, and bean. Pneumatophores used for preparation of liquor in Ecuador, and leaves used for herbal tea in Mexico and preservation of fish through smoking in Cameroon (Baba et al. 2013) Leaf, fruit, bark, and stem used in treatment of hemorrhage, hemorrhoids, rheumatism, swellings, and throat ailments (Thatoi et al. 2016) Bark, leaf, and fruit are used for astringent, malaria, and treatment for hemorrhage, rheumatism, swellings, throat ailments and diarrhea, hemorrhoids, tumors, and swellings (Sadeer et al. 2019)
16	*Avicennia marina* (Forssk.) Vierh. Avicenniaceae/*Peyarabani* *Singala bani, Tellamada, Pearabain* (Fig. 5.2)	Plant is used for firewood, construction wood, fodder, boat repair, and poles for nets/anchor (Dahdouh-Guebas et al. 2006) Astringent, smallpox, fodder, fuelwood, timber, honey collection (Pattanaik et al. 2008) Plant is used for cattle feed in India, Middle East, and Pakistan (Baba et al. 2013) Bitter aromatic juice is used in a concoction to facilitate abortion in Sundarbans (Chowdhury et al. 2014) Leaves used in treatment of rheumatism, smallpox, ulcers, and analgesic (Soman 2014)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		Bark used in treatment of skin parasites and gangrenous wounds (Rao and Murty 2014) Leaves used for rheumatism, smallpox, ulcers, and fodder for livestock (Bello and Aiyeloja 2015) Leaf, bark, stem, fruit, and seed used for rheumatism, smallpox, and skin diseases (Thatoi et al. 2016) Plasters of seed are used to cure smallpox ulceration (Goutam and Abhijit 2017) Bark astringent and used as aphrodisiac, for scabies, antifertility agent and has tanning properties. Flowers for perfumes. Leaves are aphrodisiac and used for toothache. Leaves and seeds foraged for camels and animals. Cure for skin diseases (Chitra et al. 2018) Plant is used to cure asthma, diabetes, rheumatism, and fish poison (Vinoth et al. 2019) Bark and leaf are used for smallpox, skin diseases, treatment for ulcers, and throat pains; leaf is used for ulcers, rheumatism, and burns in Iran (Sadeer et al. 2019)
17	*Avicennia nitida* Jacq. Avicenniaceae	Bark, stem, leaf, and seed are used to cure thrush, antitumor, and antiulcer (Thatoi et al. 2016)
18	*Avicennia officinalis* L. Avicenniaceae/*Nalla mada* *Nalla mada, Kalo Bani* *Karungarudal, Dhalabani,* *Kufu-beut,* *Samaedum, Pearabain* (Fig. 5.3)	Paste of hardwood used on scabies and small quantity of ash obtained after burning the wood is taken with water as antacid. The ash is also well known in Sundarbans as a detergent powder. It is a good charcoal-producing plant. Flowers are source of honey (Tribedi et al. 1993) Leaves are used for treatment of joint pains, urinary disorders, bronchial asthma, stomach disorders, and detoxification (Ravindran et al. 2005) Plant is used for firewood, construction wood, fodder, and boat repair (Dahdouh-Guebas et al. 2006) Young seed paste is used to suppress the boils Five to six raw leaves are chewed for immediate relief from constipation (Dash et al. 2007) Diuretic, leprosy, relieving ulcers, and aphrodisiac (Pattanaik et al. 2008) Heartwood decoction is given orally for fatigue (Neamsuvan et al. 2012) Plant is used for boat building (Baba et al. 2013) Tree bark used for snakebite. Leaf paste used for joint pains, knee pains, stomach disorders,

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		asthma, smallpox sores, and urinary disorders (Madhu 2013) Seed bitter, but edible. Unripe fruit is used as a remedy to treat boils (Chowdhury et al. 2014) Fruits are made into poultice and used for boils (Rao and Murty 2014) Root, bark, and seeds are used in smallpox, boils, abscess, skin parasites, and wounds (Sathe et al. 2014) Poultice of unripe seeds is applied on boils and abscess. Extract of leaves used in treatment of stomach disorders, asthma, and leprosy (Soman 2014) Roots are used as medicine for malaria. Leaves used for joint pain, urinary disorder, hepatitis, leprosy, and bronchial asthma (Bello and Aiyeloja 2015) Bark and stem used for contraceptive, astringent, diuretic, antiulcer, snakebite, rheumatism, smallpox, skin diseases, hepatitis, leprosy, antitumor, bronchial asthma, antibacterial, gastro protective, aphrodisiac, boils, and abscess (Thatoi et al. 2016) Paste of seeds is used to cure smallpox ulceration (Goutam and Abhijit 2017) Fruits are plastered on to boils and tumors, poultice of unripe seed stop inflammation, roots used for aphrodisiac, bark to treat skin problems especially scabies, resin for snakebite, and contraceptive by women, seed for ulcers (Chitra et al. 2018) Plant is used for aphrodisiac, diuretic, hepatitis, and leprosy (Vinoth et al. 2019) Fruit is used for tumor and boils; seed is used for inflammation and ulcers; root for aphrodisiac; bark for skin diseases, contraceptive, astringent, hepatitis; resin for skin diseases, contraceptive, astringent, hepatitis in Tamil Nadu, India (Sadeer et al. 2019) Leaf is used for asthma, paralysis, dyspepsia, rheumatism, ulcer, snakebite, skin disease, smallpox sores, tumor in Tamil Nadu, India; leaf for asthma, bronchial, detoxification, joints pain, stomach disorders, and urinary disorders in Pichavaram (Sadeer et al. 2019)
19	*Avicennia tomentosa* Jacq. Avicenniaceae	Bark and stem used for rheumatism (Thatoi et al. 2016)
20	*Barringtonia asiatica* L. Lecythidaceae	Seeds used as fish poison in Pacific Islands (Baba et al. 2013)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
21	*Brownlowia tersa* (L.) Kosterm. Tiliaceae/*Bola sundari*	Bark is used for family planning (Tribedi et al. 1993)
22	*Bruguiera cylindrica* (L.) Bl. Rhizophoraceae/*Kaliachua, Thua khao* (Fig. 5.4)	Timber, fuelwood, hepatitis, and tannin (Pattanaik et al. 2008) Flower decoction given orally as an expectorant (Neamsuvan et al. 2012) Leaves used for hepatitis (Bello and Aiyeloja 2015) Bark is used for hemorrhage, ulcers; bark and leaf for diarrhea, fever in Sundarbans, India; bark and root are used for diabetes, viral fever in India; stem is used for burns, intestinal worms, liver disorders in Selangor, Malaysia; leaf is used for diarrhea in Guangxi Province, China; fruit is used for shingles, eye disease, malaria in China; fruit is used for angina, hemorrhage, and hematuria in Indonesia; leaf and root for eye diseases, shingles in South Andaman Island; leaf is used for constipation in Pichavaram forest, India; whole plant is used for diarrhea, fever, burns, intestinal worms in Pichavaram, India (Sadeer et al. 2019)
23	*Bruguiera gymnorhiza* Lamk. Rhizophoraceae/*Oorudu, Kankra, Karungkandal Bandari, Thudduponna, Uredu, Kankra* (Fig. 5.5)	Plant decoction is used for washing septic wounds. Fishermen use the bark extract for coloring fishing nets to protect it against water (Tribedi et al. 1993) Plant is used for firewood, construction wood, and poles for nets/anchor (Dahdouh-Guebas et al. 2006) Firewood, timber, wood for poles, fishing traps, and fishing stakes. Hypocotyls are eaten as vegetable, fodder, wood for fishing, boat, firewood (Pattanaik et al. 2008) Leaves contain alkaloids that are tumor inhibitors. Whole-plant decoction is given twice daily after meals to relieve constipation (Madhu 2013) Plant used for fuelwood, charcoal production, and boat building (Baba et al. 2013) Propagules are eaten in Pacific Islands, yielding brownish and reddish-purple dyes in Japan, Indonesia, and Pacific Islands. Flowers used as garlands in Pacific Islands (Baba et al. 2013) Bark is macerated and the extract is said to be useful in controlling diarrhea (Chowdhury et al. 2014) Bark and fruit are eye medicine and astringent (Sathe et al. 2014) Plant is used for eye diseases (Vinoth et al. 2019)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
24	*Bruguiera parviflora* (Roxb.) Wight & Arn. ex Griff. Rhizophoraceae/*Dot*	Leaves are boiled and the decoction is administered twice a day for 1 week after meal to relieve constipation (Dash et al. 2007) Bark is used for diabetes (Sadeer et al. 2019)
25	*Bruguiera sexangula* Poir. Rhizophoraceae/*Bandari Kankra*	Bark is macerated and the extract is used to control diarrhea (Pattanaik et al. 2008) Timber, firewood, tannin, tender leaves, and hypocotyls are consumed as vegetables (Pullaiah et al. 2016)
26	*Cerebra odollam* Gaertn. Apocynaceae/*Paniamba*	Charcoal making, hemorrhage, ulcers, rheumatism, and venereal infection (Pattanaik et al. 2008) Bark and fruit used for hydrophobia, rheumatism, hemorrhage, and ulcers (Sathe et al. 2014)
27	*Ceriops decandra* (Griff.) Ding Hou Rhizophoraceae/*Gatheru, Thogaru, Garan, Garani, Gatharu, Thogara, Goran* (Fig. 5.6)	Leaf paste is applied on belly in dyspepsia for children. Juice of the leaves is given with common salt in 2:1 proportion for pain in abdomen after childbirth (Tribedi et al. 1993) Plant is used for fuelwood, construction wood, fodder, and dye/tannins for fishing nets (Dahdouh-Guebas et al. 2006) The decoction of the bark is externally applied to stop hemorrhage (Dash et al. 2007) Timber, and fruit paste are used against ulcers, fuelwood, honey collection (Pattanaik et al. 2008) Bark used for dyeing fishing nets, leaves herbal tea in India and honey and wax in Bangladesh (Baba et al. 2013) Stem is used for toothbrush and relief from toothache (Madhu 2013) The poles of the stem are used as fencing material (Chowdhury et al. 2014) Bark decoction stops hemorrhage (Rao and Murty 2014) Young leaves used for hepatitis and ulcer (Bello and Aiyeloja 2015) Plant used for hepatitis and ulcers (Vinoth et al. 2019) Bark, fruit, and leaf are used for hepatitis and ulcers in Tamil Nadu, India (Sadeer et al. 2019)
28	*Ceriops roxburghiana* Arn. Rhizophoraceae	Whole plant is used for diabetes and ulcers (Sadeer et al. 2019)
29	*Ceriops tagal* (Perr.) C.B. Rob. Rhizophoraceae/*Mat-Garan, Garani, Goran*	Root decoction is used in black fever and dysentery. Stem–bark decoction is applied to stop bleeding from fresh cuts and washing ulcers; stem bark decoction is used to stop hemorrhage (Tribedi et al. 1993)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		Purgative, stop hemorrhage, leprosy, charcoal fuelwood, shoot decoction for malaria (Pattanaik et al. 2008) Plant is used for boat building (Baba et al. 2013) Stem bark extract is used to stop hemorrhages. It is said that bark is useful for ailment that resembles peptic ulcers. The poles of the stem are used as fencing material (Chowdhury et al. 2014) Bark, shoot, and fruits are used in hemorrhage and ulcers (Sathe et al. 2014) Leaf juice is used for malaria (Khomne et al. 2018) Bark is used for hemorrhage (Sadeer et al. 2019)
30	*Conocarpus erectus* L. Combretaceae	Preservation of fish through smoking in Cameroon (Baba et al. 2013)
31	*Cynometra iripa* Kostel Caesalpiniaceae/*Singada*	Seeds are boiled and eaten during drought and stress conditions. Two to three fruits are crushed and mixed with sugar; the resulting candy is administered twice a day for 3 days for amoebic dysentery (Dash et al. 2007) Leaf decoction against ulcers (Pattanaik et al. 2008)
32	*Derris trifoliata* Lour. Fabaceae/*Kala katiranai* *Chuliakanta,* *Thopthaepnam*	Stimulant and antispasmodic (Pattanaik et al. 2008) Leaf decoction is given orally for constipation. Stem decoction is given orally for joint and muscle pain (Neamsuvan et al. 2012) Used as fish poison in Islands (Baba et al. 2013) Root is used to treat chronic alcoholism, useful as stimulant and antispasmodic (Chowdhury et al. 2014)
33	*Diospyros peregrina* Gürke Ebenaceae	Bark has traditionally been used against dysentery and intermittent fevers. Ripe fruits are used against biliousness, diseases of the blood, urinary losses, and stones in the urinary tract. Seeds and oil are given as an astringent and diarrhea. Juice of the unripe fruit is used on wounds and ulcers, it has astringent properties, and it has also been used for the treatment of diabetes Flowers and fruits are given to children with hiccough (Shariful et al. 2015)
34	*Excoecaria agallocha* L. Euphorbiaceae/*Guan* *Tilla, Gangiva, Tejbala, Genwa, Tella,*	Latex causes blisters on skin, blindness (Tribedi et al. 1993); toothache (Ravindran et al. 2005; Madhu 2013; Bello and Aiyeloja 2015; Sadeer et al. 2019); ringworm, paralysis, scabies, and

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
	Chilla, *Genwa, Thillai / Gab* (Fig. 5.7)	eczema (Dash et al. 2007); paralysis (Pattanaik et al. 2008); constipation (Neamsuvan et al. 2012); acrid and poisonous (Chowdhury et al. 2014); purgative, epilepsy, conjunctivitis (Bello and Aiyeloja 2015); abortifacient, purgative, ulcers (Mondal et al. 2016), and blindness (Goutam and Abhijit 2017) Leaf paste to treat sores and stings from marine creatures (Dash et al. 2007) Root paste to reduce swellings (Pattanaik et al. 2008) Heartwood decoction is given orally as blood tonic (Neamsuvan et al. 2012) Seeds used as fish poison. Wood smoke is anti-epileptic. Roots are used for anti-inflammation, uterotonic, purgative, epilepsy, conjunctivitis, dermatitis, hematuria, leprosy, toothache, piscicide, dart poison, swelling hands and feet, flatulence, epilepsy, anti-inflammation. Roots, branches and leaves used for epilepsy, ulcer, and leprosy (Baba et al. 2013) Leaves and stem to control stomachache, skin diseases, and loose motions (Madhu 2013) Root, branches, and leaves used in epilepsy, ulcers, and leprosy (Sathe et al. 2014) Leaf decoction for epilepsy and ulcers (Soman 2014) Roots, branches, and leaves are used for epilepsy, ulcers, leprosy, sores, emetic, purgative, and stings from poisonous marine creatures. Bark oil for rheumatism, leprosy, paralysis, conjunctivitis, dermatitis, and hematuria (Mondal et al. 2016) Plant is used for epilepsy, ulcers, leprosy, rheumatism, and paralysis (Sadeer et al. 2019) Plant is used for fuelwood, construction wood, fodder, boat repair, and poles for nets/anchor (Dahdouh-Guebas et al. 2006) Wood is used as raw material in papermaking (Baba et al. 2013) Heartwood and pneumatophores give scent (Goutam and Abhijit 2017)
35	*Finlaysonia obovata* Wall. Apocynaceae/*Panlota* *Khasai Lata, Duhi-lata*	Paste of the plants is used for bone fractures (Tribedi et al. 1993) Leaves are used in salad and asthma (Pattanaik et al. 2008) Leaf is dried and crushed and used as a remedy for dysentery (Chowdhury et al. 2014)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
36	*Heritiera fomes* Buch-Ham. Malvaceae/*Sundari, Bada sundari, Subdari* (Fig. 5.8)	Seed oil is used for piles (Tribedi et al. 1993) The bark paste is externally applied against fresh swellings (Dash et al. 2007) Stem for making poles, boat building, timber, construction purposes (Pattanaik et al. 2008) Pnuematophores used for decorative wood for indoor use (Baba et al. 2013) Seed is used for dysentery (Chowdhury et al. 2014) Root extract is used to lower down sugar levels (Goutam and Abhijit 2017) Leaf, root, and stem are used for cardiovascular diseases, gastrointestinal disorders, skin diseases, hepatic disorders, in Bhitarkanika, India; skin disease infections, jaundice, hepatitis, wound healing, diabetes, goiter in Sundarbans, India (Sadeer et al. 2019)
37	*Intsia bijuga* (Colebr.) Kuntze Caesalpiniaceae/*Masitha*	Dye, timber, furniture making (Pattanaik et al. 2008)
38	*Kandelia candel* (L.) Druce Rhizophoraceae/*Goria Sinduka*	Bark paste to reduce blood pressure (Dash et al. 2007) Charcoal, diabetes, firewood, fodder, dye used to enhance durability of fishing nets (Pattanaik et al. 2008) Medicinally useful in the treatment of frequent urination (Chowdhury et al. 2014) Bark is used in diabetes (Sathe et al. 2014) Plant is used for cardiovascular disease, cancer, neurodegenerative disorders (Sadeer et al. 2019)
39	*Kandelia rheedii* Wight & Arn. Rhizophoraceae	Plant is used for tuberculosis (Sadeer et al. 2019)
40	*Laguncularia racemosa* (L.) C.F. Gaertn. Combretaceae	Preservation of fish through smoking (Baba et al. 2013)
41	*Lumnitzera littorea* Willd. Combretaceae (Fig. 5.9)	Flowers used as garlands in Pacific Islands (Baba et al. 2013)
42	*Lumnitzera racemosa* Willd. Combretaceae/*Kripal Churunda, Farddok khao, Thanduga, Thanduga, Kadavi, Than*	Plant is used for fuelwood, construction, boat repair, fodder, and poles for nets/anchor (Dahdouh-Guebas et al. 2006) Wood powder for wounds (Neamsuvan et al. 2012) Plant is used for boat building (Baba et al. 2013) Sap from stem is used to treat rashes and itches (Chowdhury et al. 2014) Decoction of leaves used for thrush and piles (Rao and Murty 2014) Bark is used in asthma and antifertility (Sathe et al. 2014)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		Leaf powder used for antifertility, asthma, and diabetes (Bello and Aiyeloja 2015) Leaves used for snakebite and asthma (Khomne et al. 2018) Asthma, antifertility, and snakebite (Pattanaik et al. 2008) Bark used to treat asthma and in antifertility, diabetes, and snakebite. (Vinoth et al. 2019) Plant is used for snakebites, rheumatism, skin allergies, blood purifier, asthma, diabetes, and antifertility in Orissa, India (Sadeer et al. 2019)
43	*Malachra capitata* L. Malvaceae/*Ban-bhortdi*	Paste of the plant is applied on chest to cure cold and cough. It is applied on gum boils to promote suppuration (Tribedi et al. 1993)
44	*Merope angulata* (Kurz.) Sangle Rutaceae/*Banalembu*	Juice extracted from the epicarps mixed with honey is administered to treat chronic bronchitis (Dash et al. 2007)
45	*Nypa fruticans* Wurmb. Arecaceae/*Golpata* *Nipa, Goalpata*	Water in the immature fruits is used as eye-drops. Endocarp oil is used for healing wounds caused by tiger. Ash after burning the young leaves is used as antacid (Tribedi et al. 1993) Beverage, diabetes, fruit as food, thatching material, snakebite (Pattanaik et al. 2008) Plant is used to thatch roof and walling material for poultry and pig farms, and charcoal kilns, manufacture of cigarette wrappers in Bangladesh; production of beverage and sugar in Thailand; vinegar is prepared in the Philippines; popular drink nira prepared; and young seeds are edible in Southeast Asia. (Baba et al. 2013) Production of alcohol is done by fermenting fruit pulp (Chowdhury et al. 2014) Plant is used for diabetes in Malaysia and flower and leaf is used for diabetes and snakebite in the Philippines (Sadeer et al. 2019)
46	*Oncosperma tigillarium* (Jack) Ridl. Arecaceae	Plant used as poles for making houses, fish traps, jetty posts, and boats (Baba et al. 2013)
47	*Pandanus tectorius* Parkinson ex Du Roi Pandanaceae	Fruits are consumed fresh or made into various preserved foods. Plants used for handicrafts in Pacific Islands (Baba et al. 2013)
48	*Phragmites karka* (Retz.) Trin. ex Steudel. Poaceae/ *Nala*	Whole plant for fiber, fodder, making mats and fish baskets, and thatching material (Pattanaik et al. 2008)
49	*Pluchea indica* L. Asteraceae/*Ban-kupi-phul*	Plant paste is taken for dysentery Leaf paste is used in expelling guinea worms (Tribedi et al. 1993) Leaves used as herbal tea in Thailand (Baba et al. 2013)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
50	*Porteresia coarctata* (Roxb.) Tateoka Poaceae/*Dhanidhana*	Fodder, sometimes as food grain (Pattanaik et al. 2008)
51	*Rhizophora apiculata* Bl. Rhizophoraceae/*Surapunnai, Rai, Uppaponna, Kaakiponna Kongkangbailek* (Fig. 5.10)	Bark extract is used for diarrhea, nausea, vomiting, and amoebiasis, as antiseptic and to stop bleeding (Ravindran et al. 2005) Plant is used for fuelwood, construction wood, and poles for nets/anchor (Dahdouh-Guebas et al. 2006) Astringent for diarrhea, skin diseases, fodder; bark is for tanning, nausea, and fuelwood (Pattanaik et al. 2008). Fruit decoction is given orally for fever (Neamsuvan et al. 2012) Used for fuelwood (Baba et al. 2013) Plant used for charcoal and boat building (Baba et al. 2013) Wood used as a preservative to control acidity and to slow down the fermentation process and flower buds as condiment in Malaysia (Baba et al. 2013) Leaves are used in treatment of nausea, vomiting, and diarrhea. Extract of leaves used as antiseptic and used in treatment of typhoid and hepatitis (Soman 2014) Leaf and fruits are used as astringent for diarrhea, vomiting, nausea, hepatitis, and insecticides (Bello and Aiyeloja 2015) Whole plant is used for prevention of colitis, inflammatory bowel disease, and bark for amoebiasis, diarrhea, nausea, and vomiting in India (Sadeer et al. 2019)
52	*Rhizophora caseolaris* L. Rhizophoraceae/*Chinna kalinga*	Ripe fruits are edible and leaf juice is used to check hemorrhage (Rao and Murty 2014)
53	*Rhizophora conjugata* L. Rhizophoraceae /*Uppaponna*	Stem bark extract is used for controlling vomiting and diarrhea (Madhu 2013) Bark for diabetes (Sadeer et al. 2019)
54	*Rhizophora lamarckii* Montrouz. Rhizophoraceae	Extract of leaves used in treatment of liver disorders (Soman 2014) and hepatitis (Bello and Aiyeloja 2015)
55	*Rhizophora mangle* L. Rhizophoraceae	Bark is commonly used for tanning leather in Guayana. Flowers as garland in Pacific Islands and as ornamental in Japan (Baba et al. 2013) Plant is used for angina, boils, and fungal infections, antiseptic, diarrhea, dysentery, elephantiasis, fever, malaria, leprosy, minor bruises, plaster for fractured bones, and tuberculosis (Vinoth et al. 2019) Bark and leaf for diabetes in India (Sadeer et al. 2019)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
56	*Rhizophora mucronata* Lam. Rhizophoraceae/*Ponna Peykkanthal, Bhora Surapunnai, Rai Uppaponna, KongkangBaiyai*	Wood is used for fuel, construction, and poles for nets/anchor (Dahdouh-Guebas et al. 2006) Bark extract is used for controlling diarrhea, nausea, and vomiting (Ravindran et al. 2005) Freshly collected pneumatophores are made into paste and externally applied to arrest bleeding in case of hemorrhage, mouth gargling against sore throat and stomatitis (Dash et al. 2007) Hepatitis, diabetes, firewood, and tannin (Pattanaik et al. 2008) Fruit decoction is given orally for fever; bark decoction for dysentery, root decoction for dysuria, and kidney stones (Neamsuvan et al. 2012) Plant used for charcoal preparation and boat building (Baba et al. 2013) Bark is used for diabetes, leprosy, hemorrhage, and dysentery (Sathe et al. 2014) Bark is powerful astringent and used for hematoma, diarrhea, dysentery, leprosy, hemorrhage, angina, and also to cure diabetes (Rao and Murty 2014) Powder of bark is used to control diabetes. Powder of bark is applied to stop external bleeding (Soman 2014) Bark is used for diabetes, diarrhea, nausea, hematuria, hemorrhages, and angina (Shariful et al. 2015) Bark and leaves are used for elephantiasis, hematoma, hepatitis, ulcers, febrifuge, and hemorrhage (Bello and Aiyeloja 2015) Leaf juice for diarrhea and vomiting (Khomne et al. 2018) Plant is used in the treatment of hematuria, elephantiasis, hepatitis, astringent, ulcers, febrifuge, and diarrhea (Hari et al. 2019) Plant is used for elephantiasis, febrifuge, hematoma, hepatitis, and ulcers (Vinoth et al. 2019) Whole plant is used for angina, dysentery, hematuria, hepatitis, ulcers, diabetes, and hemorrhage. Bark is used for diarrhea, nausea, vomiting, amoebiasis, antiseptic, and to stop bleeding in Tamil Nadu, India. Leaf and root are used for astringent, antidote against toxic fish stings, diabetes, fever, and hypertension in Mauritius. Whole plant is used for elephantiasis, hematoma, hepatitis, ulcer, febrifuge in

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		Porong, Indonesia; leaf and root are used for angina, blood in urine, diabetes, diarrhea, dysentery, and fever in India. Leaf and root are used for childbirth, hemorrhage in Malaysia; bark is used for diarrhea in China and Japan. Leaf is used for astringent and antiseptic. Whole plant for diarrhea, elephantiasis, hematuria; stem is used for constipation, cure fertility, menstruation disorders in New Guinea. Bark is used for diarrhea, nausea, vomiting in Pichavaram, India; bark is used for diarrhea, dysentery, and leprosy in Thailand (Sadeer et al. 2019)
57	*Rhizophora racemosa* G.Mey. Rhizophoraceae/*Wéto*	Wood ash is used for cooking of food such as yam, plantain, and bean and preservation of fish through smoking in Cameroon (Baba et al. 2013) Roots used for malaria (Dossou-Yovo et al. 2017) Leaf is used for toothache, dysmenorrhea, and plant for malaria in Nigeria (Sadeer et al. 2019)
58	*Rhizophora stylosa* Griff. Rhizophoraceae	Plant is used as fabric in Japan; flowers are used as garland in Pacific Islands; and plants are sold as souvenirs in Japan (Baba et al. 2013)
59	*Salicornia brachiata* Roxb. Chenopodiaceae/*Kattumari Batula*	Whole-plant ash is used for itches (Ravindran et al. 2005) Leaves and young shoots are eaten (Pattanaik et al. 2008) Leaf and stem extracts are used for treating hepatitis (Chitra et al. 2018) Plant is used for hepatitis (Vinoth et al. 2019)
60	*Salvadora persica* L. Salvadoraceae/*Miriga*	Leaf juice is rubbed on jaws to strengthen teeth and gums (Dash et al. 2007) Leaves are used in salads, leaf decoction for asthma, cough, and rheumatism (Pattanaik et al. 2008) Root, shoot, bark, and leaves used against snakebite, rheumatism, and tonic (Sathe et al. 2014)
61	*Scyphiphora hydrophyllacea* Gaertn. Rubiaceae/*Tagri Bani*	Shoot extract is warmed slightly and used for enteric diseases and also used to treat liver ailments (Chowdhury et al. 2014)
62	*Sesuvium portulacastrum* L. Aizoaceae/*Godabani, Nunia*	Plant paste is applied on burns and wounds. Leaf paste is taken for gonorrhea (Tribedi et al. 1993) Young plants are edible after boiling to remove excess salt from body (Pattanaik et al. 2008) Plant is eaten in Asia Pacific (Baba et al. 2013)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		Whole plant is used to remove salt from body and high blood pressure (Khomne et al. 2018) Plant is used for hepatitis (Vinoth et al. 2019)
63	*Sonneratia alba* J. Smith. Sonneratiaceae/ *Orua*	Skin disorders, vegetable, fodder, timber, fuel-wood (Pattanaik et al. 2008) Plant is used in boat preparation (Baba et al. 2013) Fruit is used in hemorrhage and swellings (Sathe et al. 2014)
64	*Sonneratia apetala* Buch.-Ham. Sonneratiaceae/*Peddakalinga, Keora, Keruan,Kaling, Kyalanki, Kero, Keora* (Fig. 5.11)	Plant is used for firewood, construction wood, and fodder (Dahdouh-Guebas et al. 2006; Pattanaik et al. 2008) Leaf paste is applied on cuts and wounds Fruits are edible (Pattanaik et al. 2008) and eaten both raw and cooked (Tribedi et al. 1993); they are made into chutney and eaten by the local people (Dash et al. 2007) Fruit juice is used for hysteria. Honey and wax are produced from this plant (Baba et al. 2013) Fermented juice to check hemorrhage (Rao and Murty 2014) Fruit is used as spice and to improve flavor of cooking (Chowdhury et al. 2014) Fruits are rich in vitamin C and used to prepare juices, curries, etc. (Goutam and Abhijit 2017) Used for epilepsy, conjunctivitis, dermatitis, hematuria, leprosy, purgative, and toothache (Chitra et al. 2018)
65	*Sonneratia caseolaris* (L.) Engl. Sonneratiaceae/*Chinna kalinga, ChakKeora* *Orua, Kalinga(Peda), Kandia, Lam phu, Ora*	Plant is used for firewood, construction wood, and fodder (Dahdouh-Guebas et al. 2006) Leaf decoction is used against diarrhea, fuel-wood, and vegetable (Pattanaik et al. 2008) Root powder is used for topical/herpes simplex. Raw fruits are given orally for wounds and diarrhea (Neamsuvan et al. 2012) Fruits are used for the preparation of beverages in Sri Lanka, syrup in Indonesia, and fruit drink in Maldives (Baba et al. 2013) Poultice of fruits is applied on sprains and swellings. Used as astringent and antiseptic. Used in treatment of piles and stopping hemor-rhage (Soman 2014) Fruits are edible and used to prepare a local cuisine which is valued for its sour taste. Fruit extract is used as anthelmintic (Chowdhury et al. 2014) Ripe fruits are edible, and leaf juice is used to check hemorrhage (Rao and Murty 2014)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		Fruits are rich in vitamin C and used to prepare juices, curries, etc. (Goutam and Abhijit 2017)
66	*Sonneratia griffithii* Kurz. Sonneratiaceae/ *Ora*	Fruit is used as spice and to improve flavor of cooking (Chowdhury et al. 2014)
67	*Suaeda maritima* Dumort Chenopodiaceae/*Giria saga, Maniagash* (Fig. 5.12)	Young twigs are good laxative. Cooked plants are eaten at the time of scarcity (Tribedi et al. 1993) Hepatitis and leafy vegetable (Pattanaik et al. 2008) The juice of this herb is used for liver diseases by Arab practitioners. Leaves also used as remedy for liver, heart, and lipid disorders (Chitra et al. 2018) Plant is used for hepatitis (Vinoth et al. 2019)
68	*Suaeda monoica* Forssk. ex J.F. Gmel. Chenopodiaceae/*Nilavumari*	Leaves used as edible green leaves, hepatitis, and ointment for wounds (Chitra et al. 2018) Leaf for hepatitis (Vinoth et al. 2019)
69	*Suaeda nudiflora* Moq. Chenopodiaceae	Leaves are used in ophthalmia and emetic (Sathe et al. 2014)
70	*Xylocarpus granatum* Koen. Meliaceae/ *Kalinga* *Dhudul, Dhundul* *Somunthiri, Sisumar* *Chenuga, Dhundul,* *Ta boon, Dhundul*	Plant is used for fuelwood, construction wood, and boat repair (Dahdouh-Guebas et al. 2006). Wood is durable and used for making furniture (Chowdhury et al. 2014) Wood for handcrafts and buttress roots for decorative material (Baba et al. 2013) Seed oil is used to promote growth of hair, rheumatism, and breast tumor (Tribedi et al. 1993) Bark extract cures dysentery. Seed oil is used as illuminant of hair. Bark decoction is used for curing diarrhea and cholera (Ravindran et al. 2005) Seed oil is popularly used as mosquito repellent and to treat insect bites (Dash et al. 2007) Malaria, timber, firewood, and insect bite (Pattanaik et al. 2008) Bark decoction is given orally for mucous and bloody dysentery and diarrhea (Neamsuvan et al. 2012) Bark used for diarrhea and dysentery. Seed paste is applied on mumps, boils, and swollen breasts and toothache (Rao and Murty 2014) Bark extract is used to treat dysentery Leaves, seeds, and bark are used for treating jaundice, cholera, dysentery, fever, cough in the newly born child, dysentery, tonic, astringent, for breast cancer, cholera, diarrhea (Sathe et al. 2014)

(continued)

Table 5.1 (continued)

No.	Botanical name/Family/Vernacular name	Uses
		Bark used for cholera, fever, malaria, diarrhea; leaves for microbial diarrhea; fruits for hyperglycemia, dyslipidemia, and diarrhea (Das et al. 2014) Bark is used to treat fever, cholera, colic, diarrhea, and other abdominal affections. Fruits for diarrhea and externally to soothe inflammation. Seeds are used in tonics, and the bitter and astringent oily fluid (Shariful et al. 2015) Bark, leaves used for fevers malaria, cholera (Bello and Aiyeloja 2015) Bark extract is used to cure dysentery and diarrhea (Goutam and Abhijit 2017) Plant is used for cholera, diarrhea, elephantiasis, inflammation, pain, swelling of breasts; bark is used for cholera, diarrhea, fever, malaria in East Africa; leaf is used for diarrhea in South East Asia; fruit is used for diarrhea, dyslipidemia, hyperglycemia in Indian coastal regions; bark is used for cholera, diarrhea, and dysentery in Pichavaram, India; and bark is used for cholera in Thailand (Sadeer et al. 2019)
71	*Xylocarpus mekongensis* Pierre. Meliaceae/ *Parus Pitamari, Dhundul*	Wood is good for furniture making (Chowdhury et al. 2014) and a source of tannin (Pattanaik et al. 2008) Bark: Malaria, diarrhea, antinociceptive activities, inflammation antioxidant, bark extract is used to cure dysentery and diarrhea (Goutam and Abhijit 2017) Fruits**:** Elephantiasis, preventing swelling of the breast (Das et al. 2014)
72	*Xylocarpus moluccensis* (Lamk.) Roem. Meliaceae/*Pitakorua*	Firewood, malaria fever, tannin extraction (Pattanaik et al. 2008) Plant is used for boat building, wood handcrafts. Honey and wax produced in Bangladesh (Baba et al. 2013) Bark for fever, malaria, astringent, febrifuge, dysentery, diarrhea. Leaves for cancer and inflammation. Fruits for aphrodisiac, elephantiasis and swelling of breasts, bactericidal, hyperglycemia, and dyslipidemia (Das et al. 2014)

Fig. 5.1 *Acanthus ilicifolius*

Fig. 5.2 *Avicennia marina*

Fig. 5.3 *Avicennia officinalis*

Fig. 5.4 *Bruguiera cylindrica*

Fig. 5.5 *Bruguiera gymnorhiza*

Fig. 5.6 *Ceriops decandra*

Fig. 5.7 *Excoecaria agallocha*

Fig. 5.8 *Heritiera fomes*

Fig. 5.9 *Lumnitzera littorea*

Fig. 5.10 *Rhizophora apiculata*

Fig. 5.11 *Sonneratia apetala*

Fig. 5.12 *Suaeda maritima*

5.2.2 Non-Wood Forest Products

Mangroves are also an important resource for a wide range of non-wood forest products (Spalding 2004; Walters et al. 2008; Spalding et al. 2010). The mangrove palm *Nypa fruticans* is commonly used for the production of thatch, beverage, sugar, alcohol, and vinegar in Southeast Asia. Production of mangrove honey is an important economic activity in countries such as Bangladesh, Vietnam, Cuba, and Guyana. Mangrove foliage is used as fodder for camels and cattle, notably in Pakistan, the Middle East, and India. Harvesting of mangrove bark for tannin as dye remains a viable economic activity in countries of the Asia–Pacific region. Dahdouh-Guebas et al. (2006) reported the use of *Ceriops decandra* bark, to color and preserve fishing nets in East Godavari delta of Andhra Pradesh, India.

5.2.3 Medicinal Uses

Mangrove species with medicinal properties are also harvested as herbal remedies by coastal communities in some countries (Baba et al. 2013). Mangroves provide a wide domain for medicinal uses, most yet to be explored. Nature's nurse, healing properties are attributed to *Rhizophora* trees in popular/folk medicine in which root, leaf, and stem extracts have inhibitory properties affecting the growth of various human pathogenic organisms (Hernandez and Perez 1978). The bark of red mangrove trees has been used in the folk remedy for a wide array of diseases (Duke and Wain 1981). Different mangrove species have different wood and bark properties, making some more suitable than others for specific uses (FAO 1994). For example, the genus *Avicennia* comprises 8 species of mangrove trees that occur in intertidal zones of estuaries and sea beds found in tropical and temperate regions spanning throughout the world. Different parts of the plants have ethnomedicinal applications for treatment of various diseases such as asthma, cancer, diabetes, malaria, rheumatism, smallpox, and ulcers (Baba et al. 2016). Pharmacological investigations have revealed antimicrobial, antioxidant, anticancer, antidiabetic, anti-inflammatory activities, and so on in these plants. The genus possesses some unique metabolites of varied chemical classes, which are responsible for their wide range of pharmacological activities (Thatoi et al. 2016). Das et al. (2014) reviewed ethnomedicinal, antimicrobial, and antidiarrheal studies carried out on different species of *Xylocarpus* and the ethnomedicinal uses include fever, malaria, cholera, diarrhea, swelling of breast, encephalitis, inflammation, dyslipidemia, pain, hyperglycemia, etc. From the Americas, *Laguncularia racemosa,* a white mangrove in Florida, USA, was used as a tonic to treat fevers, skin wounds, ulcers, dysentery, and scurvy and to prevent tumors. In addition, the leaves were used as a source of minerals (Andreu et al. 2010). From Africa, Dossou-Yovo et al. (2017) observed 14 species of mangroves covering 13 genera and 13 families used by the local people from Ouidah to Grand-Popo districts of Southern Benin for curing 9 diseases and disorders mainly malaria. Neamsuvan et al. (2012) found 35 species of mangroves in Sating Phra Peninsula, Songkhla Province, Thailand, used mostly for curing fever, skin diseases, and gastrointestinal tract problems. Shariful et al. (2015) reported 6 species used in traditional ayurvedic medicinal treatment for various types of eruptions, gastrointestinal infections, etc., in Sundarbans mangrove forests of Bangladesh. Bello and Aiyeloja (2015) documented 19 species covering 10 families used for medicinal purposes like flatulence, epilepsy, smallpox, malaria, diabetes, fever, and hepatitis in Nigeria.

India has a long tradition of using mangrove plants in medicines and has been well documented. Ravindran et al. (2005) presented information on 11 species of mangroves used for therapeutic purposes like snakebite, smallpox, ulcer, detoxification, birth control, urinary disorders, stomach disorders, tumor inhibitors, jaundice, malaria, toothache, skin diseases, diarrhea, nausea, vomiting, cholera, etc., by the Periyapattinavar, Irular, and fishermen communities of Pichavaram, Tamil Nadu. Chitra et al. (2018) also reported the traditional medicinal uses of 6 species of mangroves present in the backwaters of Muttukadu, Tamil Nadu. Hari et al. (2019) reported *Rhizophora mucronata* for its uses by the folklore of Tamil Nadu in treating angina, dysentery, and hematuria. Dash et al. (2007) emphasized the therapeutic uses of 28 mangrove species used in the treatment of 22 different diseases, viz. snakebite, smallpox, ulcer, birth control, urinary disorder, stomach disorder, jaundice, malaria, toothache, skin diseases, diarrhea, vomiting, cholera, bone fracture, and constipation by the inhabitants of Bhitarkanika Wildlife Sanctuary, Orissa. Pattanaik et al. (2008) also provided information on traditional products and medicinal uses of 51 taxa of mangrove plants from Bhitarkanika Wildlife sanctuary. Madhu (2013) reported the use of 7 species of mangroves for curing various ailments, aches, and disorders in Coringa Wildlife Sanctuary, East Godavari district, Andhra Pradesh. Ten species of medicinal plants were recorded in the mangrove areas of Andhra Pradesh for curing different diseases like snakebite, rheumatism, skin diseases, birth control, smallpox, gangrenous wounds, hemorrhage, piles, hematoma, diarrhea, dysentery, leprosy, angina, diabetes, mumps, boils, swollen breasts, and toothache (Rao and Murty 2014). A total of 21 species of mangrove plants was studied by Sathe et al. (2014) in Southern Konkan region of Maharashtra for ethnobotany and curing various diseases. Soman (2014) reported the use of 8 species of mangroves used for curing dyspepsia, snakebite, skin diseases, kidney disorders, rheumatism, smallpox, ulcers, boils, abscesses, stomach disorders, asthma, leprosy, epilepsy, diarrhea, nausea, vomiting, typhoid, hepatitis, diabetes, external bleeding, sprains and swellings, and hemorrhage by the folklore of coastal Maharashtra. Chowdhury et al. (2014) reported 31 species of mangroves for curing a variety of ailments including ulcers, boils, stomach problems, urinary diseases, and others in central part of Indian Sundarbans. Acharya (2015) reported Rhizophoraceae mangroves of Coastal Odisha to be an astringent, emmenagogue, expectorant, hemostat, styptic, and tonic; red mangrove is a folk remedy for angina, asthma, backache, boils, constipation, convulsions, diarrhea, dysentery, dyspepsia, elephantiasis, eye ailments, fever, fungal infections, headaches, hemorrhage, inflammation, jaundice, kidney stones, lesions, malaria, malignancies, rheumatism, snakebites, sores, sore throat, syphilis, toothache, tuberculosis, ulcers, and wounds. Goutam and Abhijit (2017) listed 11 mangrove species used for curing boils, snakebite, bone fracture, diarrhea, dysentery, diabetes, etc., by the folklore of Sundarbans, West Bengal. Khomne et al. (2018) and Vinoth et al. (2019) have also presented the therapeutic and traditional uses of mangrove species to treat for example asthma, diarrhea, headache, malaria, piles, ulcers, wounds, joint pains, paralysis, hepatitis, leprosy, eye diseases, antitumor, antifertility, and tuberculosis.

5.3 Discussion

Coastal populations in particular are directly or indirectly dependent upon mangrove resources for socio-economic and personal needs. Commercial and traditional products of mangroves are diverse and include commodities such as timber, fuelwood, thatching materials, charcoal, medicines, food, and fodder (Hamilton and Murphy 1988; Choudhury 1989). Mangroves are biochemically unique, producing a wide array of novel natural products. Substances in mangroves have long been used in folk medicine to treat diseases (Bandaranayake 1998).

This review deals with 72 species of mangroves covering 42genera and 29 families used by the folklore mostly residing in coastal regions globally treating a variety of diseases and for other purposes. Rhizophoraceae is the dominant family with 8 species followed by Avicenniaceae (7 spp.); Combretaceae, Meliaceae, Chenopodiaceae, Sonneratiaceae (4spp each); Apocynaceae, Acanthaceae (3 spp. each); Pteridaceae, Malvaceae, Caesalpiniaceae, Rutaceae, Arecaceae, Poaceae (2spp. each); and others with one species each. The ailments cured include abscess, angina, asthma, backache, blood dysentery, boils, cancer, cholera, cold, constipation, convulsions, diabetes, diarrhea, diuretic, dog bite, dyslipidemia, dysentery, dyspepsia, elephantiasis, epilepsy, encephalitis, eruptions, external bleeding, eye ailments, fever, flatulence, fungal infections, gastrointestinal infections, gout, hasten the expulsion of placenta after childbirth, headaches, hematuria, hemorrhage, hepatitis, hyperglycemia, inflammation, itch, jaundice, joints pain, paralysis, kidney stones, leprosy, lesions, leucorrhea, malaria, malignancies, nausea, piles, rheumatism, smallpox, snakebites, sores, sore throat, sprains and swellings, stomach disorders, swelling of breast and pain, syphilis, toothache, tuberculosis, typhoid, ulcers, vomiting, and wounds. Traditional and indigenous systems of medicine persist all over the world (Kalita and Bikash 2004). The unique traditional system of healthcare progressed from generation to generation within the society is still prevalent within the remote rural areas of the country. It is evident that the local inhabitants of mangrove forest have good knowledge about the phytomedicine. However, in recent decades many mangrove areas have been depleting, because of their extensive and rapid deforestation, industrial development, fisheries, aquaculture, and human settlement. In many countries, local communities rely on mangrove forest products to meet their subsistence needs for fuel and construction.

5.4 Conclusions

Tropical coastal populations, particularly in developing countries, can be highly dependent on the mangrove ecosystem for multiple purposes (Bandaranayake 1998; Ewel et al. 1998; Dahdouh-Guebas et al. 2000). Firstly, the mangroves form a natural protection against cyclones and floods, which is realized more in villages "facing the cyclones at the frontline." They prevent oceanic cyclones, soil erosion, and sea surges and constitute an important ecological asset and economic resource of the coastal marine environment. They are also used as the breeding and feeding grounds for fishes. Thus, they constitute an important ecological asset and economic resource of the coastal marine environment (Deshmukh and Balaji 1994). Secondly, the mangrove ecosystem provides them with direct natural resources, such as fuel and construction wood, fodder for cattle and fishery-related activities. It is clear that the information of traditional knowledge about the medicinal values of mangroves coincides with authentic reports of antimicrobial properties of mangroves. The medicinal plants listed in Table 5.1 may be subjected to intensive phytochemical screening and pharmacognosy in search of new leads for modern herbal drugs.

Mangrove forests are getting degraded due to high anthropogenic activities. People are extracting plants for different medicinal and economic values. So, day by day, the mangrove forests are disappearing. Conservation of the present vegetation and natural regeneration of the species having medicine and other socio-economic importance should be done as top priority. Many economic plants belonging to mangroves have become threatened due to overexploitation and various human activities. Steps should be taken for in situ and ex situ conservation of existing mangrove vegetation. Increased human needs, commercial activities, and urban development demands are leading to rapid conversion of mangrove forest vegetation. Therefore, sound management strategies are urgently needed to conserve the mangroves for their ethnobotanical values.

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Chapter 6
Mangrove Ecosystems and Their Services

Sudhir Chandra Das, Shreya Das, and Jagatpati Tah

Abstract An ecosystem is a dynamic community consisting of biotic (microorganisms, plants and animals) and abiotic components (water, air and soil), each interacting with one another. Each ecosystem and its components play a key role in maintaining our environmental balance and human health both directly and indirectly from the goods, outputs and processes that natural and managed ecosystems provide us. Ecosystem services are the many and varied benefits to human beings provided by ecosystems and can be classified into supporting, regulating, provisioning and cultural services. Mangrove ecosystems provide many important services to coastal communities such as coastal protection from storms and flooding and provision of fish and seafood. Mangroves are also important in carbon capture and for global climate regulation. Quantification of ecosystem service values for mangroves could help with their protection for the future.

Keywords Abiotic · Biotic · Ecosystem services · Environment · Function · Human well-being

6.1 Introduction

Ecosystem services are the outputs, conditions or processes of natural systems that directly or indirectly benefit human well-being or enhance social welfare. In many ways, ecosystem services can benefit people, either directly or as inputs into the production process of other goods and services. For example, the pollination of crops by bees and other insects largely contributes to food production, hence considered as an ecosystem service directly contributing to social welfare. Another example is the

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protection provided by the riparian buffers and wetlands which attenuate the flooding in residential areas. The term "ecosystem services" was only conceptualized during 1970s.

Ecosystem services are not traded directly in the market; the benefits derived from them are not fully reflected in market activities. Thus, excessive depletion of natural capital (abiotic and biotic components of the ecosystem) and ecosystem services takes place due to unregulated market. During the eighteenth and nineteenth centuries, land and other natural resources were recognized as productive assets by economists. One of the founding works of the U.S. conservation movement was the *Man and Nature* (1864) by George Perkins Marsh and was among the first writings to formally characterize relationships between natural and social systems. He proclaimed that large-scale damage to the natural systems by anthropogenic activities would diminish human welfare. Quantification of ecosystem service values has its foundation in formal economic methods for non-market valuation, which have been refined extensively since their initial development by environmental and resource economists in the 1940s. By the early twenty-first century, ecosystem services analyses paid greater attention to issues such as the complex relationships between ecological and socio-economic systems, how changes in those relationships affect human well-being, to what extent the values of different types of services can and should be quantified in monetary terms and the most-suitable approaches to quantify the different types of services. The United Nation's Millennium Ecosystem Assessment (2005), which evaluated the consequences of ecosystem change, concluded that humans have degraded the ability of the Earth's ecosystems to support social welfare. In response, ecosystem services should now influence policy decisions and governments should recognize the full range of costs and benefits associated with the actions affecting those services.

Mangroves play a crucial role in sustaining coastal ecology and securing coastal communities. They curtail the harmful effects of coastal erosion, storms and flooding and are one of the most cost-effective methods of disaster management along coastlines. A number of tangible and intangible benefits such as safe and healthy environments, many forest products and a wide variety of seafood can also be provided by the mangrove forests. Mangroves absorb and sequester three to four times more carbon than terrestrial forests. Mangroves have a critical contribution to climate regulation through carbon capture. They store most carbon in their root systems and neighbouring soil but terrestrial forests store most of their carbon in the trunk and branches; thus, mangroves act as better carbon "sinks," locking it away for generations. Also, the risk of wildfire and associated loss of stored carbon is much less likely to occur unlike terrestrial forests, making them a safe long-term carbon "investment."

Mangrove ecosystem services are worth an estimated US$ 33–57 thousand per hectare per year to the national economies of developing countries with mangroves (Duke et al. 2014). Vo et al. (2012) emphasized the role of goods and services provided by mangrove ecosystem contributing towards human welfare directly and indirectly. Similarly, Mojiol et al. (2016) supported that knowing the economic value of ecosystem services is an important asset because a major demand is to support human well-being, sustainability and distributional fairness. In the absence of mangrove forests, people who rely on the mangroves would suffer from a lack of forest products and food security, especially in fisheries, reduced crop yield and the direct impact of natural disasters. Hence, the loss of a mangrove forest would negatively affect several developmental activities.

6.2 Understanding the Ecosystem

Ecosystem is a segment of nature/biosphere consisting of a community of living organisms (biotic) and the physical environment (abiotic) both interacting and exchanging materials between them. Ecosystem is natural if developed under natural conditions without human support (e.g. forest, grassland, sea). It is artificial/man-made if the ecosystem is created and maintained by human beings (e.g. agriculture or agro-ecosystem is the largest man-made ecosystem). Flow of energy and transfer of materials occur commonly from one ecosystem to another, e.g. transfer of detritus and soil from terrestrial to aquatic ecosystems, catching of aquatic animals by humans, birds and other terrestrial animals. Every ecosystem is composed of two types of basic components, namely biotic and abiotic.

6.2.1 Biotic Components

They include all living beings present in an ecosystem, namely producers, consumers and decomposers. The components are connected through food, its contained energy and a web of inter-relationships.

1. *Producers*: They are autotrophs that manufacture organic compounds from inorganic raw materials with the help of solar energy. Producers convert solar energy into chemical energy. Besides food, producers give out oxygen to the atmosphere and take in carbon dioxide from the atmosphere. Major producers are photosynthetic bacteria, green algae, bryophytes, pteridophytes and vascular plants. In terrestrial ecosystems, producers are generally rooted plants, but in aquatic ecosystems, phytoplankton is the major producers.
2. *Consumers*: They are heterotrophs which feed on plants/animals. First-order consumers (herbivores, e.g. deer, cattle, rabbit and insect) feed on producers. Second-order consumers (e.g. frog, fox, snake, wild cat, peacock and owl) feed on herbivores. Third-order consumers (mostly carnivores, e.g. tiger and lion) feed on second-order consumers. Energy flows in the ecosystems through different tropic levels.
3. *Decomposers*: They are saprotrophs which decompose the organic remains after the death of organisms by secreting extracellular digestive enzymes. They are

also known as mineralizers as they release minerals trapped in organic remains. Detritivores are decomposers as well as scavengers.

6.2.2 Abiotic Components

Abiotic components or physical factors are the non-living components of the ecosystem. They are light, temperature, air, rainfall/water and soil.

1. *Light*: Sun is the source of light, and it provides energy for photosynthesis and hence primary productivity. Upper leaves of a tree receive more light than the lower leaves. Floating hydrophytes show higher productivity than the submerged ones. Photoperiods influence flowering, leaf fall, migration and breeding.
2. *Temperature*: Four life zones are recognized on the basis of temperature, viz. tropical, subtropical, temperate and arctic/alpine. Both in hot and in cold areas, plants have adaptations to reduce transpiration and retain water.
3. *Rainfall/water*: Amount and periodicity of rainfall along with temperature regime determine the type of terrestrial ecosystem, namely tropical rain forest, tropical deciduous forest, temperate broadleaved forest, temperate coniferous forest, scrub, grassland and desert. Water helps in minerals and food transportation in plants.
4. *Soil*: Soil is the major source of organic and inorganic substances. The dead remains and excreta of organisms are called organic detritus which are decomposed by the decomposers to release inorganic nutrients. These nutrients are taken up by the microorganisms and plants for their body cell formation. Soil supports the plant growth. Type of vegetation is determined by soil type, soil pH and soil fertility.
5. *Air*: Air consists of one of the main life-sustaining gases called oxygen. Almost all living beings breathe in and breathe out air. Air is present both in atmosphere and in soil. It helps in respiration of the organisms. Plants take in carbon dioxide from air for photosynthesis and release oxygen in the air during the process.

6.3 Underlying Ecology

A strong foundation in ecology is required to understand ecosystem services, as ecology describes the basic principles and interactions of the environment with its organisms. The descriptive characterization of material and energy flow between them has become one of the greatest challenges since the scale of interaction varies not only from milliseconds to millions of years but also from microbes to landscapes. For example, in the case of a forest ecosystem, the combined contribution of the detritus upon the forest floor, the soil microbes and soil physico-chemical properties towards the abilities of that forest for providing ecosystem services like carbon sequestration, water purification and erosion prevention is indispensable. In addition, the same forest plays an important role to provide habitat for other organisms and a facility for human recreation, which are also ecosystem services. Thus, multiple benefits when clubbed together and the benefits of targeted objectives are secured,it generate some ancillary benefits. In order to understand the inter-relationship of different organisms with the ecological processes surrounding them, the complexity of Earth's ecosystem appears to be a great challenge. To study the ecosystem services related to human ecology, Kremen (2005) proposed a research agenda which includes the following steps:

1. Identification of ecosystem service providers (ESPs), i.e. populations or species which provide specific ecosystem services and characterization of their functional roles and relationships;
2. Determination of community structural aspects influencing ESP function in their natural landscapes, such as compensatory responses that stabilize function and non-random extinction sequences which can erode it;
3. Assessment of key environmental (abiotic) factors affecting the provision of services;
4. Measurement of the spatio-temporal scales of ESPs and their services acting on.

The evaluation process of ESP functionality has been standardized and improved recently by quantifying the relative importance of different species in terms of their efficiency and abundance (Balvanera et al. 2005). These parameters are useful to indicate the response of different species towards environmental changes (i.e. climate, resource availability and predators). One of the major limitations of this technique is that it does not consider the effects of interactions which are often both complex and fundamental in maintaining an ecosystem. Nevertheless, to obtain a better knowledge of the resilience of an ecosystem amidst environmental changes, it is essential to estimate its functional structure integrating with the information about individual species.

Ecologists also believe that biodiversity can stabilize the provision of ecosystem services. With the increase in biodiversity, the variety of ecosystem services available to the society also increases. Hence, to manage the natural resources and their services, it is essential to understand the relationship between biodiversity and ecosystem's stability.

6.4 Types of Ecosystem Services

The United Nations Millennium Ecosystem Assessment (MA) defined ecosystem services as "the benefits people obtain from ecosystems." They also delineated four categories of ecosystem services, viz. supporting, regulating, provisioning and cultural (Table 6.1).

Table 6.1 Ecosystem services

Supporting	Regulating	Provisioning	Cultural
Nutrient cycling	Carbon sequestration and climate regulation	Food (including seafood and game), crops, wild foods and spices	Cultural (including use of nature as motif in books, film, painting, folklore, national symbols and advertising)
Primary production	Purification of water and air	Raw materials (including lumber, skins, fuel wood, organic matter and fodder)	Spiritual and historical (including use of nature for religious or heritage value of nature)
Soil formation	Predation regulates prey populations	Genetic resources (including crop improvement genes and health care)	Recreational experiences (including ecotourism, outdoor sports and recreation)
Groundwater recharge	Waste decomposition and detoxification	Water purity	Science and education (including use of natural systems for school excursions and scientific discovery)
Habitat provision	Carbon dioxide and oxygen balance in air	Biogenic minerals	Therapeutic (including eco-therapy, social forestry and animal-assisted therapy)
Pollination	Pest and disease control	Medicinal resources (including pharmaceuticals, chemical models and test and assay organisms)	
	Flood regulation	Energy (hydropower, biomass fuels)	
		Ornamental resources (including fashion, handicraft, jewellery, pets, worship, decoration and souvenirs like furs, feathers, ivory, orchids, butterflies, aquarium fish and shells).	

6.4.1 Supporting Services

Supporting services are the services that support life forms in the ecosystem and allow the other ecosystem services to be present such as food supply, soil formation and water purification. Slade et al. (2019) outlined a direct relationship between the number of species and ecosystem services, i.e. the greater the number of species, the greater is the ecosystem services. Ecosystems not only provide shelter and habitats for numerous plant and animal species but also maintain their diversity and provide them food and water essential for their survival. The wide variety of life forms on earth helps to maintain genetic diversity on our planet. These services last over a long period of time and have indirect impacts on human beings. Several services can be considered as being both supporting services and regulating/cultural/provisioning services (Table 6.1).

Primary production refers to the production of organic matter from inorganic raw materials, i.e. chemically bound energy through processes such as photosynthesis and chemosynthesis. The organic matter synthesized by producers forms the basis of all food webs. Further, it generates oxygen (O_2), a molecule necessary to sustain animals and humans (Wratten et al. 2013). On an average, a human consumes about 550 L of oxygen per day, whereas plants produce 1.5 L of oxygen per 10 g of growth.

Nutrient cycling is the cyclic movement of nutrients from inorganic forms in the environment to the organic forms in living organisms and back to inorganic forms by decomposer after the death of living organisms through an ecosystem by the interaction of its biotic and abiotic components. The ocean or seas are a huge storage pool for these nutrients, namely carbon, nitrogen, phosphorus, calcium and magnesium. The nutrients are absorbed by the planktonic organisms of the marine food web and are transferred from one tropic level to the other and from one ecosystem to the other. Nutrients are recycled through the life cycle of organisms as they die and decompose by the action of decomposers, thereby releasing the nutrients into the neighbouring environment. The service of nutrient cycling eventually impacts all other ecosystem services as all living beings require a constant supply of nutrients to survive (Molnar et al. 2009).

Groundwater can reduce salinity and increase nutrient availability which can enhance plant growth and alter plant biomass allocation pattern (Hayes et al. 2018).

Pollination is one of the most crucial services that biodiversity provides. Two of nature's key pollinators are insects and wind; without these two pollinators, growing agricultural crops would be a challenge for us. In fact, researchers have found that pollinators improve crop yields by approximately 75% worldwide!

6.4.2 Regulating Services

Regulating services are the benefits derived from the regulation of ecosystem processes. In the case of coastal and estuarine ecosystems, these services include climate regulation, carbon sequestration, waste treatment and disease regulation and natural hazard regulation acting as buffer zone.

6.4.2.1 Climate Regulation

Both the biotic and abiotic assemblages of marine ecosystems play a vital role in climate regulation. They act as sponges when it becomes gases in the atmosphere, retaining large levels of CO_2 and other greenhouse gases (methane and nitrous oxide). Marine plants also use CO_2 for photosynthesis and help to reduce the atmospheric CO_2. The oceans and seas absorb heat from the atmosphere and redistribute it through water currents and atmospheric processes, like evaporation. The reflection of light also allows the cooling and warming of the overlying atmosphere. The ocean temperatures are thus imperative to the regulation of the atmospheric temperatures in any part of the world; without the ocean, the Earth would be unbearably hot during the daylight hours and frigidly cold, if not frozen, at night (Molnar et al. 2009).

6.4.2.2 Carbon Sequestration and Air Quality

Trees and forests play a crucial role in our lives. They provide shade, influence rainfall, promote the availability of water and help to regulate air pollution. Forested ecosystems play a vital role in regulating weather and climate by storing carbon and other greenhouse gases. Trees remove more carbon from the atmosphere as they grow older, which helps to keep our planet cool. Side by side, it releases oxygen in the atmosphere during photosynthesis which improves air quality.

6.4.2.3 Waste Treatment and Disease Regulation

Another service provided by the marine ecosystem is the treatment of wastes, thereby helping in the regulation of diseases. Wastes can be diluted, decomposed and detoxified in course of transport through marine ecosystems; pollutants are removed from the environment and stored, buried or recycled in this ecosystem. Marine ecosystems break down organic waste with the help of microbes that filter water, reduce the effects of eutrophication and break down toxic hydrocarbons into their inorganic components such as carbon dioxide, nitrogen, phosphorus and water (Molnar et al. 2009). The fact that waste is decomposed and diluted with large volumes of water and moves with water currents leads to the regulation of diseases and the reduction of toxic substances in seafood.

6.4.2.4 Carbon Dioxide and Oxygen Balance in Air

Plants are autotrophs and perform the role of producer in ecosystem. Producers are also called transducers as they transform solar energy into chemical energy bonded in the organic compound manufactured in the process. They produce food for the animal kingdom through photosynthesis and release oxygen into the air to be taken up by the animals during respiration. In turn, when animals produce carbon dioxide during respiration, the plant kingdom intakes it for food production and supply oxygen to the air. This way plants and animals maintain the balance of carbon dioxide and oxygen in the air.

6.4.2.5 Regulation as Buffer Zones

Coastal and estuarine ecosystems act as buffer zones against natural hazards and environmental disturbances, viz. floods, tidal surges, cyclones and storms. They absorb a portion of the impact and thus lessen its effect on the land. Wetlands (which include saltwater swamps and salt marshes) and the vegetation it supports (trees and root mats) retain large amounts of water (surface water, snowmelt, rain and groundwater) and then slowly release them back, decreasing the likeliness of floods.

6.4.3 Provisioning Services

These services are also known as ecosystem goods. Provisioning services consist of all "the products obtained from ecosystems." Our environment provides us with materialistic resources essential for our physical well-being and various economic activities. These are known as provisioning services (viz. raw materials, food, shelter, energy and other resources).

Ecosystems provide the appropriate conditions and environments to grow important food crops such as vegetables, fruits, pulses and rice. In addition to that, human beings also rely greatly on freshwater and marine resources as well as wild animals living in forested ecosystems for meat.

Forests produce a large type and variety of timber products, including round timber, sawn timber, panels and engineered wood, e.g. cross-laminated timber as well as pulp and paper (FAO 2020a). Besides the production of timber, forestry activities may also result in products that undergo little processing, such as firewood, charcoal, wood chips and round timber used in an unprocessed form (FAO 2020b). Global production and trade of all major wood-based products (sawn timber, wood pulp, wood-based panels, wood charcoal and pellets) recorded their highest ever values in 2018 (FAO 2019).

Forests also provide non-timber forest products which include fodder, tubers, aromatic and medicinal plants and wild foods. About one billion people worldwide depend to some extent on wild foods such as wild meat, edible insects, fishes, edible plant products and mushrooms which usually contain high levels of key micronutrients. The value of forest foods as a nutritional resource is not only limited to low- and middle-income countries but more than 100 million people in the European Union (EU) also regularly consume wild food. Marine and coastal fisheries accounted for 12 per cent of world food production in 2000 (Molnar et al. 2009). Fish and other edible marine products provided to the populations living along the coast, primarily fish, shellfish and seaweeds, constitute the main elements of the local cultural diets, norms and traditions.

Marine creatures provide us with the raw materials needed for the manufacturing of clothing, building materials (lime extracted from coral reefs), ornamental items and personal-use items (art and jewellery). Humans have use marine environments for the production of renewable energy; e.g. power of waves or tidal powers are used as a source of energy for the powering of a turbine. Oceans and seas are used as sites for offshore oil and gas installations, and offshore wind farms.

Biochemical resources are compounds extracted from marine organisms for use in medicines, pharmaceuticals, cosmetics and other biochemical products. Genetic resources are the genetic information found in marine organisms that are used for animal and plant breeding and for technological advances in the biological field. These resources are either directly taken out from an organism, namely fish oil as a source of omega3 or used as a model for innovative man-made products. The construction of fibre-optic technology based on the properties of sponges is used for the benefit of mankind. Marine-sourced products tend to be more highly bioactive compared with terrestrial products due to the fact that marine organisms have to retain their potency despite being diluted in the surrounding seawater (Molnar et al. 2009).

6.4.4 Cultural Services

Apart from materialistic goods and services, ecosystems also provide us with cultural non-materialistic services with recreational, cognitive, aesthetic and spiritual values, which are not easily measured in monetary terms. Several communities across the world even consider forests sacred, and in many countries, they worship certain tree species such as *Ficus religiosa*, *Ocimum sanctum*, etc.

Marine ecosystems have been used by many people as an inspiration for their works of art, music, architecture, traditions, etc. Water environments are spiritually important because a lot of people consider them as a means for rejuvenation and change of perspective. Many also consider the water as being a part of their personality, if they have lived near it since their childhood. Living near water bodies for a long time not only results in a certain set of activities that become a ritual in the lives of people but also of the culture in the region.

Sea sports (surfing, snorkelling, whale watching, kayaking, recreational fishing) are very popular among coastal populations. A lot of tourists also travel to resorts close to the sea or rivers or lakes to experience these activities and relax near the water. The United Nations Sustainable Development Goal 14 also has aimed at enhancing the use of ecosystem services for sustainable tourism especially in Small Island Developing States.

Knowledge can be acquired from marine processes, environments and organisms which could be implemented into our daily actions and into the scientific domain, although much is yet to be known about the ocean world because of its extraordinary intricacy and complexity and how it is influenced by large spatial scales, time lags and cumulative effects (Molnar et al. 2009).

It has been observed that ecosystems provide humans and other life forms with several services essential for their survival. Ever-increasing human populations over the past few centuries pose a severe threat to these critical services. The mindless abuse and over-exploitation of natural resources have contributed to the rapid extinction of thousands of species, in addition to causing widespread deforestation, leading to climate change and environmental pollution. Unfortunately, it is hard to quantify or place a price tag on these services.

6.5 Mangrove Ecosystem Services

Mangroves provide a highly productive and biologically rich ecosystem which acts as a source of food and habitat for a wide range of species, many of which are endangered. Mangrove forests serve as feeding and breeding grounds for mammals, reptiles and migratory birds and provide crucial habitats for commercially important fish and crustacean species. The roots of the mangrove physically buffer shorelines from the erosive actions of ocean waves and storms. Additionally, they absorb floodwaters and slow down the flow of sediment-loaded river water, thereby protecting riparian zones. As a result of this sedimentation process, the potentially toxic waste products contained in the water get settled down at the bottom, thereby improving the quality of water and sanitation in coastal communities. de Lacerda (2002) depicted the mangrove ecosystem services (Fig. 6.1).

Mangroves provide a wide range of benefits (ecosystem services) to human populations (Ellison 2008; Barbier et al. 2011). Coastal communities have long relied on the provisioning services of mangroves, such as the extraction of construction materials and fuelwood (Chow 2018) and the capture of food sources namely finfish and shellfish (Ellison 2008; Carrasquilla-Henao et al. 2019). Coastal

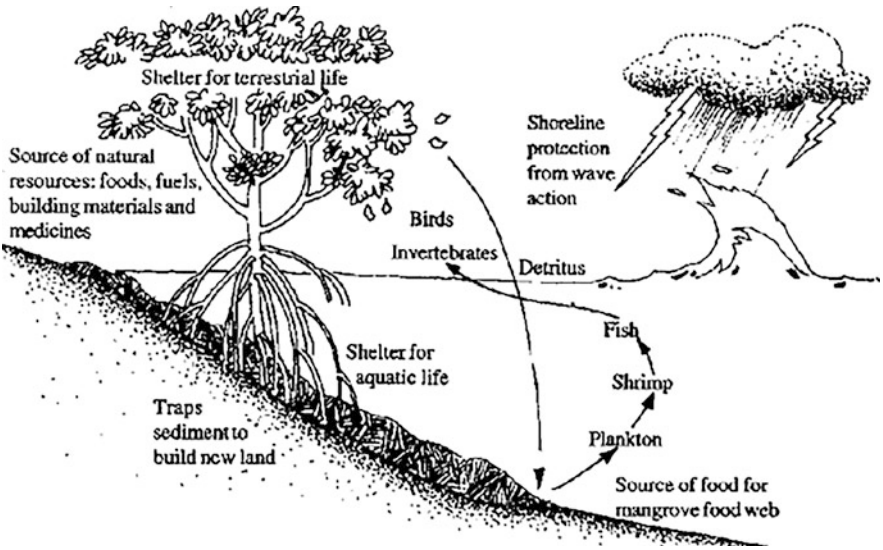

Fig. 6.1 Ecosystem services of Sundarbans (source: de Lacerda 2002)

communities also derive cultural ecosystem services from mangroves, including tangible services such as recreation and intangible services such as aesthetic appeal and spiritual values (Thiagarajah et al. 2015; Spalding and Parrett 2019). Mangroves also offer a wide range of regulating services, in addition to coastal protection (Ranjan 2019; Horchard et al. 2019), pollutant assimilation (Tam and Wong 1995) and macroclimate regulation and mitigation of global climatic change through carbon (C) storage and sequestration (Adame et al. 2018). Some regulating services (e.g. coastal protection) accrue directly to co-located coastal communities, whereas others (e.g. regulation of macroclimate) benefit the global commonwealth.

Although mangroves consist of less than one per cent of worldwide tropical forests, they are highly precious ecosystems, catering an array of essential goods and services on which the livelihoods, well-being and security of coastal communities are endowed. The intricate root system of mangroves helps to reduce wave energy, prevent erosion and shield coastal communities from the devastating tropical storms. Mangrove ecosystems support the livelihoods of thousands of coastal communities by providing not only firewood and timber but also seafood which is essential for both subsistence consumption and the local and national seafood trade. Apart from these direct benefits, mangroves also play an important role in global climate regulation. On average, they store around 1000 tonnes of carbon per hectare in their biomass and underlying soil, making them some of the most carbon-rich ecosystems on the planet (Duke et al. 2014). Despite its value, the mangrove ecosystem is one of the most threatened on the planet. Mangroves are being destroyed at three to five times the average rate of forest loss. As a consequence of land conversion for agriculture and aquaculture, coastal development, pollution and over-exploitation of mangrove resources, more than a quarter of the original mangrove cover has already disappeared. This grievous situation will lead to diminishing of important ecosystem goods and services. The repercussion of further mangrove degradation will be oppressive for the well-being of coastal communities in developing countries, especially where people rely heavily on mangrove goods and services for their daily subsistence and livelihoods. Understanding the importance of mangrove ecosystems for both biodiversity and human welfare can be the driving force to conserve, better manage and restore these ecosystems worldwide. Some of these have been successful at regional scales supported by national policies that recognize the significant long-term benefits of mangroves over short-term financial gains. As mangroves are valuable socio-economic and ecological resources, the government should frame and enforce policies to curb the widespread losses from anthropogenic activities as well as to conserve and manage it sustainably.

6.6 Conclusions

Mangroves are socio-ecological systems whose functions provide a wide range of ecosystem services. The mangrove ecosystem is a vital hub of the marine environment due to nutrient fluxes, productivity and biodiversity of organisms. It protects the coastal zone from natural calamities and ensures pollution abatement, and it performs recycling of nutrients. The values of mangroves are significant in providing forestry and fisheries products to sustain the coastal livelihood and economy. However, pressures of coastal development, aquaculture and agriculture without sufficient enforcement of the legislation have resulted in the destruction of mangroves in many places. Hence, there is an urgent need to conserve the momentous ecosystem for global well-being; otherwise, the ecosystem services and other benefits provided by the mangroves will be diminished or lost forever (Duke et al. 2007).

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Chapter 7
Mangrove Forests and People's Livelihoods

Sudhir Chandra Das, Shreya Das, and Jagatpati Tah

Abstract Mangrove forests in estuarine areas are rich in varied resources, supporting the livelihoods of people living in and around these forests. Mangroves act as a barrier against cyclones, storms and tidal surges which protect the people and their livelihoods in the area. Mangrove forests provide a major source of fuelwood, fodder, and timber and mangrove wetlands harbour fish, crabs and other edible invertebrates. The finfish, shellfish and other food sources obtained from mangroves play a vital role in the food security of coastal communities. Other minor uses of mangroves include collection of medicinal plants, collection of molluscs, shells for lime making, honey, wax, etc. Coastal communities have strong economic bonds with the coastal ecosystems with which they interact and interfere in various ways. However, as mangrove soils are fertile, mangrove forests have also been cleared for agriculture and prawn farming purposes. Conservation of mangrove ecosystems by involving the local community through, for example, Joint Forest Management and sharing of benefits with them is the best approach. Economically, mangroves support livelihood opportunities for coastal communities through fisheries but alternate income generation activities should be incorporated such as mushroom cultivation, apiary and ecotourism so that livelihood strategies can be diversified to sustain local livelihoods and reduce their dependency on forest resources for the protection, conservation and management of mangrove resources.

Keywords Coastal community · Livelihood · Wetland · Mangrove forest · Finfish · Shellfish

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7.1 Introduction

Livelihood is the means of making a living. It encompasses people's capabilities, activities, income and assets required to secure the necessities of life. A livelihood is sustainable when it can cope with and recover from stress and shocks, maintain or enhance its capabilities and offer sustainable livelihood opportunities for the next generation, which comes up with net benefits to other livelihoods at the local and global levels in the long run (Orinya 2016).

Many poor people in developing countries depend heavily on forests and wetlands for their livelihood because of lack of other alternative means to support their subsistence (Ngomela 2007). Local inhabitants depend on forest resources for various products like fuelwood, construction materials, medicines and food. While the contribution of environmental goods and services to rural livelihoods is widely documented (Chhetri et al. 2015), their significance within forest-dependent communities remains insufficiently explored although mangrove forests are considered to contribute significantly to the local economy of the people living both near and far of it.

Mangrove wetlands are distinguished features of the coastal regions of tropical countries. They consist of a mangrove forest and its associated waterbodies. A mangrove forest nurtures a group of plant species that grow well in the intertidal areas where the substratum is composed of accumulated deposits of river-borne sediment (Selvam et al. 2010). Wetlands are important repositories of biological diversity and are among the world's most productive ecosystem. They help to regulate water flows, remove sediments and pollutants and provide essential habitats for diverse fauna. They are threatened in many parts of the world by drainage from agriculture or urban expansion, conversion to aquaculture ponds, overgrazing and in forested logging (Mohanty and Mohapatra 2018).

The mangrove wetland is a multipurpose ecosystem that accomplishes several protective, productive and economic functions to sustain the ecological and livelihood security of the coastal communities. Mangrove forests and their associated wetlands:

1. Act as a barrier against cyclones and prevent entry of saline water inland during storm surges,
2. Act as buffer against floods and prevent coastal erosion,
3. Provide nursery grounds for numerous commercially important fish, prawns, crabs and molluscs,
4. Enhance fishery production of nearby coastal waters by exporting nutrients and detritus,
5. Provide habitats for wildlife ranging from migratory birds to estuarine crocodiles.

The economic value of the mangrove wetland is based on (1) availability of wood products ranging from timber, poles, posts to firewood, (2) availability of non-wood products such as fodder, honey, waxes and thatching materials and (3) availability of aquatic products such as fishes, prawns, crabs, molluscs, clams and oysters.

However, the mangroves all along the coasts are threatened due to the high density of population in these areas and competing demand for agricultural land and prawn farming (Mohanty and Mohapatra 2018). Livelihood in these villages is agriculture and fishing. In the lean period, people generally migrate to other villages for wage labour and brick kiln work (Orinya 2016). Mangrove forests provide different kinds of benefits to local people like jobs and incomes often needed to supplement inadequate returns from agriculture; products such as fuelwood, fodder, food and building materials for the home; and a wide variety of environmental benefits, without which other activities might be impossible.

7.2 The Importance of Mangroves to People

Mangroves are typical tropical forests, that uniquely emerged at the dynamic interface of land and sea. They are found in coastal and estuarine areas throughout the tropics and to some extent in subtropical countries and are capable of thriving in saltwater, thriving in a condition to which only a few species have adapted. Mangroves constitute the foundation of a highly productive and biologically rich ecosystem which provides shelter and feeding grounds for a variety of species, many of which are endangered. Worldwide mangroves constitute less than 1% of all tropical forests; they are important ecosystems, accomplishing an array of essential goods and services which contribute significantly to the livelihood security and well-being of coastal communities. The complex network of mangrove roots can help to diminish wave energy, limiting erosion and protecting coastal communities from the devastating tropical storms. Mangrove ecosystems are mostly used as an essential source of seafood for both subsistence consumption and the local and national seafood trade, in addition to providing other materials namely firewood and timber, which provide the livelihoods of thousands of coastal communities.

Apart from these direct benefits, mangroves also play a vital role in global climate regulation. On average, they capture and store around 1000 tonnes of carbon per hectare in their biomass and underlying soil, making them some of the most carbon-rich ecosystems on the planet (Duke et al. 2014). Despite its value, the mangrove ecosystem is one of the most threatened on the planet. Mangroves are being destroyed at an alarming rate of three to five times greater than average rates of forest loss and over a quarter of the original mangrove cover has already been destroyed due to land conversion for agriculture and aquaculture, coastal developmental works, pollution and over-exploitation of mangrove resources. This grievous situation will lead to a diminishing of important ecosystem goods and services. The repercussion of further mangrove degradation will be oppressive for the well-being of coastal communities in developing countries, especially where people rely heavily on mangrove goods and services for their daily subsistence and livelihoods. However, the future of mangroves should not be at stake. Increasing recognition of the importance of mangrove ecosystems for both biodiversity and human well-being is driving efforts around the world to conserve, better manage and restore these ecosystems. Many of these have been successful at a local scale, often supported by national policies that recognize the significant long-term benefits of mangroves over short-term financial gains. It is to be understood that mangroves are valuable for the socio-economic and ecological resource of the region and should be managed and conserved sustainably. This will take a commitment by governments to make policy decisions and enforce existing protection measures to curb the widespread losses from human activities.

7.3 Socio-economic Profile of Villages in and Around Mangroves

In general, the villages in and around mangroves have a high percentage of socially disadvantaged groups. The level of literacy as well as per capita income is much lower than in other parts of the country. The infrastructure in the villages is poorly developed with hardly any metalled roads making it difficult to pass in heavy rains. The main mode of transport and communication is mainly by boat. Electricity is patchy. Primary health centres and schools are also inadequate.

In the absence of any major industry in the area, the vocation can broadly be divided as cultivators 26.5%, agricultural labour 47%, household worker 1.5% and others 25% which include fishermen, crab collectors and honey collectors (Pramanik and Nandi 1999). Almost 50% of the agricultural workers are also fishermen and crab collectors in lean periods of agriculture. The majority of farmers fall under the category of small and marginal groups. The rich people in the village mainly invest in agricultural land and commercial fishing by engaging the poor fishermen to earn high profits. Moneylenders also abound in the villages. They give advances to fishermen and honey collectors in return for which they take all the fish caught and honey collected, respectively, for a pittance. Most of the villagers also have a cattle population, which are reared not for milk supply but to fulfil their protein requirements.

Mangroves in Myanmar extensively grow throughout the coastal strip of the country, providing ecosystem goods and services to coastal communities as well as all other parts of the country. The study by Aye et al. (2019) shows that 43% of total household income is generated through selling of forest products collected from the mangrove forest such as firewood, fishes, crabs and prawns, whereas agricultural and non-farm incomes were found to be 25% and 32% of total income, respectively. The results also reveal that incomes from the mangrove forest products for fish, crab, prawn and firewood are specifically 36%, 28%, 9% and 27%, respectively, confirming the dependence of the local livelihoods on the mangrove forest ecosystem.

7.4 Dependence on Mangrove Forest Resources

Local people depend on forest resources for various products such as fuelwood, construction materials, medicines and food. Globally, it is estimated that between 1.095 billion and 1.745 billion people depend to varying degrees on forests for their livelihoods and about 200 million indigenous communities are almost fully dependent on forests (Chao 2012). Moreover, 350 million people who live adjacent to dense forests depend on them for subsistence and income (World Bank 2006; Chao 2012).

The mangrove forest dependence level of rural households was calculated using the relative forest income (RFI) as a ratio of total forest income to total household income account derived from the consumption and sale of mangrove forest resources. This was derived (Langat et al. 2016) as

$$\mathrm{RFI} = \mathrm{TFI}/\mathrm{THI}$$

where THI is the total household income and TFI is the total forest environmental income. If the level of dependence of the family is greater than 25% in the study area, then they are dependent on forest resources. The higher the percentage, the greater is the forest resource dependence.

The majority of the people's livelihoods in Myanmar mangrove areas were at a subsistence level, and they heavily depended on natural resources (Aye et al. 2019). Major livelihood activities in these sites were agriculture, non-farm activities and mangrove forest product collection. Among them, mangrove forest resources were the major income source and most of the coastal communities relied on them. The main provisioning sources, shelter, fodder, medicines and a fishery are important for subsistence, livelihood and commercial fisheries for the communities living in coastal and delta areas. The income for the local poor communities living in rural areas of developing countries was less than US$ 1/day and they rely on the ecosystem services (Barbier 2012). Their income (43% to total household income) was generated by selling forest products collected from the mangrove forest such as fishes, crabs and prawn. So, half of the respondents were engaged in mangrove-based occupations because they are poor and predominantly live in the delta region.

Levels of dependence on forest resources around the world among households with access to forests vary from 6 to 65% depending on the local circumstances. Singh et al. (2010) in Bangladesh estimated that the contribution of non-timber forest products—NTFPs—is 79% on average to the annual income of the collector's family. Clinton et al. (2016) inferred in their study in Nigeria that 85% of households depended on mangrove resources for their income and agricultural income was estimated a 25% of total income. Paddy fields were the major cultivation, and seaweed cultivation was rapidly emerging as another cash crop in the coastal area carried out predominantly by women. Non-farm incomes accounted 32% of total household income. Major non-farm activities were wage labour in mangrove forest plantations, casual and seasonal labour in agriculture, salary, private shop, etc.

Furthermore, mangrove forest dependencies vary among different income levels. It is seen that households with middle-income and low-income levels are the most dependent on forest resources with 52.8% and 79.4% of total household income because most of the middle-income and low-income level households are landless and they do not have other alternative income activities.

The lack of industries coupled with high population density has led to a high level of resource dependency. Dire poverty is the primary reason for people venturing into the forests braving risks like man-eating tigers and other fierce animals, frequent cyclones and storms. Every year some of these people, who enter into the forest in the Sundarbans, fall prey to the tiger. They enter the mangrove forests for fishing, honey collection and fuelwood collection. However, many miscreants often take the guise of fishermen and enter the forests with the intention of poaching and felling of timber species. Though in the past, people would enter the forest for collection of *Nypa fruticans* and *Phoenix paludosa* leaves used for thatching; these practices have since been discontinued. Local inhabitants are traditionally dependent on mangrove forests for the following items.

7.4.1 Fuelwood and Timber Collection

People living near mangrove forests enter to collect fuelwood and at times timber. The main species collected in India is *Ceriops decandra*. The sticks from these trees were used for fencing purposes and thicker ones for posts of houses. *Avicennia* spp., which has a high calorific value, were also cut for fuelwood. Most of the mangroves have little timber value except *Xylocarpus* and *Heritiera* species. However, currently these activities have been stopped inside the forests after the formation of JFM Committees under Joint Forest Management system in India. The introduction of LPG in villages for cooking has also helped reduce the collection of fuelwood and timber from forests.

7.4.2 Fishing and Crab Collection

Fishing and crab collection (Fig. 7.1) are important activities in coastal mangrove areas, with 40–50% of the local inhabitants in Myanmar and India dependent on this activity. Fishermen enter into the mangrove areas for fishing after taking permits from the nearest forest office, although sometimes they enter the forests without permission. These permits are given for a specific time and area which is mentioned in the permits. These permits are issued against registered Boat License Certificates (BLCs). In the Sundarban Tiger Reserve, there are about 923 Boat License Certificates or Fishing Permits, out of which 75% are active and 25% are lying inactive due to various administrative and technical reasons. However, some irregularities

Fig. 7.1 Fishing in rivers (above) and crab collection (below) in mangrove areas

have been noticed like the fishermen usually extending their period of stay in the forest area after expiry of permit times and trying to enter non-permitted areas.

7.4.3 Shrimp Collection

Tiger prawn shrimp (*Penaeus monodon*) collection (Fig. 7.2) was one of the popular livelihood activities in mangrove areas of the Sundarbans as they are the nursery grounds. This activity was mostly carried out by women and was a grave threat as many were attacked by crocodiles. It also had a negative impact on the aquatic biodiversity as the tiger prawn collection resulted in the destruction of at least 50 other species of finfish and shellfish. However, this livelihood activity has been heavily discouraged now after the formation of Joint Forest Management Committee due to its negative impact on the ecosystem. Thus, presently only a handful of people are involved in this activity.

Fig. 7.2 Tiger prawn shrimp collection by netting in Raimangal River in Sundarbans

7.4.4 Honey Collection

Rock bees (*Apis dorsata*) from the Himalayas visit the Sundarbans Forest every year during the summer months the main flowering season for mangroves and because most of the mangrove flowers are highly nectar bearing. Flowering starts with the bloom of *Aegiceras corniculatum* from March and is followed by the flowering of *Acanthus ilicifolius*, *Avicennia* spp., *Sonneratia apetala* and *Rhizophora* spp. This continues for 2 months during April and May. The density of honey depends on the number of salt excretory glands available on the tree. *Aegiceras corniculatum* having 19 glands/mm^2 which gives the best honey. As rock bees are migratory so the experiment of setting up apiaries with rock bees has failed. The best mangrove species to produce honeycomb are *Excoecaria agallocha* (39%) followed by Bain (*Avicennia* spp.) 16%, Goran (*Ceriops* spp.) 11%, Garjan (*Rhizophora* spp.) 10%, Keora (*Sonneratia* spp.) 10% and others bear only 14%. The ideal site for construction of hives would be *Excoecaria* and *Phoenix* combination of forests.

Honey collection teams require permits from the forest department to move on to the mangrove forests (Fig. 7.3). On detecting a honeycomb, the honey collectors smoke out the bees using torches of *Phoenix* leaves called "Bolen" (a bunch of leaves). They take care not to damage the eggs, larva, etc., which are found in the comb. The honey collectors come back to the same comb after 15 days and again cut them. The second time the yield is normally 60% that of the first time. One of the drawbacks of Sundarban honey is that it contains more moisture than honey obtained from other areas due to which it ferments quickly.

Fig. 7.3 Wild honey collection team in Sundarbans (left—team is moving out to forests and right—team returned after collection of honey)

7.4.5 Collection of Plant Parts for Medicine

Mangroves are important natural resources that are able to provide a wide range of goods and services for the local community. Further, chemical compounds and extracts of mangroves can be used mainly for folk medicine (Bandaranayake 1998). *Rhizophora* seedlings are able to cure a sore mouth. The bark extract of *Bruguiera sexangula* is effective against two tumours of sarcoma 180 and Lewis lung carcinoma (Sasidhar et al. 2013). Extracts from the bark of *Rhizophora mucronata* and the leaf of *B. cylindrica* show antiviral activity against all the viruses tested. Extracts from the leaves, barks, stems and roots of *Ceriops tagal*, *C. decandra*, *Xylocarpus granatum*, *X. moluccensis*, *R. mucronata* and *R. apiculata* have shown to have anti-stringent, anti-diarrhoea and haemostatic properties (Sasidhar et al. 2013). Extracts from the mangroves have been applied in the treatment of health disorders for centuries.

7.4.6 Ecotourism

Ecotourism can be defined as "responsible travel to natural areas that conserves the environment, sustains the well-being of the local people and involves interpretation

Fig. 7.4 Visiting tourists in boats (left), estuarine crocodile (right up) and Royal Bengal tiger (right down)

and education." Ecotourism can also build a culture of environmental respect and protection while providing positive experiences to visitors and hosts. On the host's side, an ecotourism mindset is one generating value for local people and the industry, and they should help deliver remarkable experiences to visitors while raising their sensitivity to local environmental, political or social issues. The tourists can enjoy nature, mangrove forests along with its flora and fauna (Fig. 7.4). In mangrove areas particularly in estuaries, ecotourism is a popular business.

Local people can be involved to a large extent in ecotourism and can earn a lot. They can run canteens at eco-resorts of the forest department by supplying food and refreshments to the tourists and the income from food and refreshments goes directly to the local people. The trained and educated youth can be engaged as "Nature Guides." The State Forest Department provides training and the guide charges collected from the tourists go direct to the guides. Local people can earn from tourists by providing boats or launches for them for their visit and the hiring charge goes to the owner.

7.5 Factors Influencing Forest Dependency

Local households in these areas are mainly dependent on the forest resources for their livelihood activities. The factors responsible for their forest dependence are as follows:

1. Agricultural land holding,
2. Household size and.
3. Education level.

7.5.1 Agricultural Land Size

Agricultural land size in Myanmar is positively correlated with mangrove forest income (Aye et al. 2019). This result is contradictory to the general findings of other studies. In Ethiopia, the relative income from the forest was negatively correlated with cropland (Babulo et al. 2009). Lebmeister et al. (2018) observed that non-timber forest produce (NTFP) dependency in the rural household was significantly decreased with increasing farmland. In order to maintain agricultural incomes and food production, farmers have resorted to cultivating even more land (UNEP 2009). For instance, in coastal areas, converting mangrove areas to rice farms has resulted in seawater encroachment and salinization of soils, providing a source of income for only a short period of time before yields drop below economic levels (UNEP 2009).

7.5.2 Household Size

Household size is directly related to forest income. As the household size increased, the dependency on mangrove forest resources of the household also increased. Ways of accessing mangrove forest products are the main determinant of being dependent on mangrove forest products. It is found that 65% of respondents produced mangrove forest products directly and the remaining 35% produced indirectly (Aye et al. 2019).

7.5.3 Education Level

Education level impacted negatively on mangrove forest dependence because they have less access to alternative income sources (Mulatie and Tesfaye 2018). This means that forest income of the non-educated household is greater than the educated one and shows that a household with educated members is less dependent on forest resources as a means of livelihood income.

In a study in Ethiopia, most respondents were extremely dependent on the forest regardless of the gender of the head of the household, similar to the finding of Abdullah et al. (2016) in Bangladesh. Similarly, it found a negatively significant correlation with mangrove forest income. So, if the households have other alternative livelihood sources, their dependency on mangrove forest will decrease.

7.6 Alternate Livelihood Potential in Mangrove Areas

Alternate livelihood programmes are a widely used term for interventions that aim to reduce the prevalence of activities in forests deemed to be environmentally damaging by substituting them with lower impact livelihood activities that provide at least equivalent benefits. Potential alternative livelihoods in mangrove areas are as follows:

7.6.1 Mushroom Cultivation

Mushrooms have been recognized universally as a nutritious food crop and can be cultivated on a commercial scale as a supplementary source of income but the lack of knowledge about the new resource hinders the entire process. Production of mushrooms has gradually created a special appeal to customers all over the globe. Its cultivation is one of the most profitable agribusinesses that can be started with a low investment. It is growing gradually as an alternative source of income for many people. Button mushrooms, oyster mushrooms and paddy straw mushrooms are the three major types of mushrooms used for cultivation. All these mushrooms of commercial importance are grown by different techniques. Button mushroom and oyster mushroom (Fig. 7.5) are grown in the winter season whereas paddy straw mushrooms can be grown in temperatures from 35 °C to 40 °C from June to October. Mushrooms are grown in special beds known as compost beds. Spawns (mushroom mycelium) can be obtained from certified national laboratories. Spawning can be done in two ways either by scattering the compost on the bed surface in the tray or else by mixing the grain spawns with compost before filling the trays.

7.6.2 Apiculture

Apiculture is the art of rearing honeybees using modern scientific methods. In this method, the bees are bred commercially in apiaries. The bees are taken care of and managed to produce honey and wax. The main season of apiculture is from March to June every year which is the flowering season of mangroves. Apiculture (Fig. 7.6) is a safe and sustainable method of producing honey, whose collection in the wild is a very risky process as the Sundarban mangrove is inhabited by tigers and there is every chance of a tiger attack on people who are going for wild honey collection. With the help of World Wildlife Fund—India (WWF-India), apiaries are being developed on a large scale by involving Self-Help Group (SHG) members in the Sundarbans. In recent times, large-scale training regarding rearing of bees and marketing of honey has been provided to traditional collectors. The bee species used in apiculture is *Apis mellifera*. This species can produce a yield up to 60 kg/

Fig. 7.5 Cultivation of oyster mushroom during winter

Fig. 7.6 Apiculture: setting of bee boxes (left) and beehives in the boxes (right)

hive/year whereas *Apis indica* produces lesser quantity of honey to the tune of 20–25 kg/hive/year. The response of the community to this programme is excellent.

7.6.3 Pisciculture in Ponds

The breeding, rearing and transplantation of fish by artificial means are called pisciculture or fish farming. It is the principal form of aquaculture. It involves raising fish commercially in tanks or ponds for food (Fig. 7.7). Demand for fish and fish protein is increasing which has resulted in widespread overfishing in wild fisheries. In the last three decades, aquaculture has been the main driver of the increase in fisheries and aquaculture production, with an average growth of 5.3% per year from 2000 to 2018, reaching a record of 82.1 million tonnes in 2018 (FAO 2020). This is a

Fig. 7.7 Newly dug up (left) and existing (right) ponds for fish farming

very good source of alternative livelihood. Fishing in the wild (e.g. seas, bays and estuaries) involves lots of risks of storms and other extremities but fish farming has no such risks.

7.6.4 Coconut Cultivation

Coconut (*Cocos nucifera* L.) is a cash crop in coastal areas. Coconut cultivation is a lucrative business for the inhabitants of the coastal belt. It acts as a shelterbelt along the foreshore or coastline. It is essentially a tropical plant growing mostly between 20°N and 20°S latitudes. The ideal temperature for coconut growth and yield is 27 ± 5 °C and humidity >60%. A well-distributed rainfall of about 200 cm/year is best for proper growth and higher yield. Under favourable conditions, tall coconut palms start flowering after 5 years of planting and dwarf varieties after 3 years of planting, while the fruit fully ripens after 10–12 months. The Joint Forest Management Committee (JFMC) and Self-Help Group (SHG) members have been involved in this alternate income generation activity. Figure 7.8 shows the distribution of coconut seedlings in the Sundarbans after devastating Amphan cyclonic storm in May 2020.

Fig. 7.8 Coconut seedlings distribution after Amphan cyclonic storm in Sundarbans

7.6.5 Fruit and Vegetable Vending

The selling of vegetables door to door by a van or rickshaw helps people working in different offices that do not have time to go to the market in the morning. Vegetable vending is a good alternate way of income generation activity for the beneficiary. Some of the poor people in the coastal mangrove areas can be employed in this mode of income generation. Fruit and vegetable vending machines/vans are also devised by different companies for providing higher humidity required to maintain the freshness in fresh fruits and vegetables even under normal conditions.

7.6.6 Grocery Shop

A grocery shop is another alternative livelihood option for household income generation. Grocery items are always in demand throughout the year in every locality. People living in and around the mangrove forests can be employed themselves individually or in group. It can be a retail shop or online mode with a wide range of products from food grains, oil and masalas to fruits and vegetables at competitive prices where local quality can be trusted.

Fig. 7.9 Poultry farming by a villager

7.6.7 Poultry and Livestock Farming

Poultry farming is a form of animal husbandry which rears domesticated birds such as chickens, ducks, turkeys and geese to produce meat or eggs for food. Poultry, mostly chickens, are farmed in great numbers for quick earning. Chickens reared for eggs are known as layers while chickens reared for meat are called broilers. Initially, each willing member may be given 50–100 chicks for rearing; subsequently, they can increase the bird number by selling the initial stock (Fig. 7.9). Necessary training may be provided from the forest department side to save the adjoining forests by reducing pressure on the forest.

7.7 JFM and Livelihood Options

In India, the Joint Forest Management (JFM) provides an opportunity for managing forest resources for better productivity and availability of forest produce. The mangrove forest provides direct benefits (physical products such as wood, food, medicine, fuel, fodder, fibre, organic fertilizers and a host of other products) and indirect and attributable benefits for environmental enrichment. As an inseparable component of the total land use systems, forestry has significant inter-relationships with agricultural, pastoral and food-producing systems. Through soil and water conservation and maintenance of soil fertility, the mangrove forest provides critical support for agricultural development. In addition, forest-based small and cost-effective enterprises can help increase rural employment and raise the income and living standards of rural people including forest dwellers and indigenous groups. The

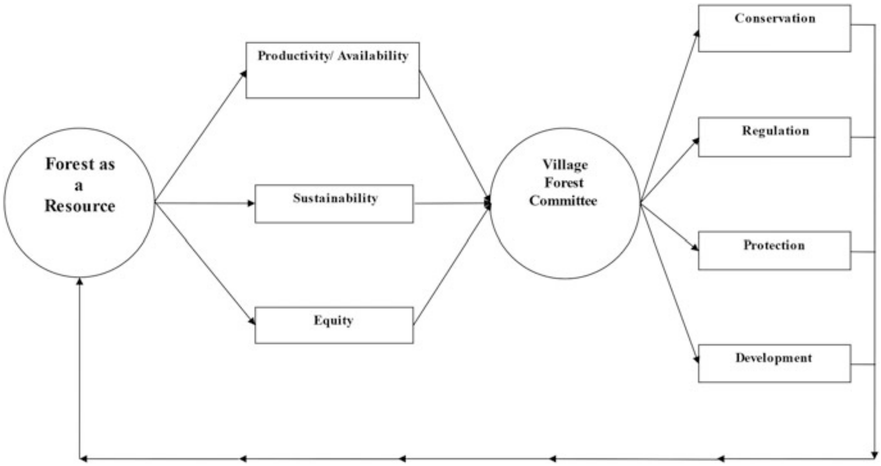

Fig. 7.10 Resource cycle (Source: Biswas 1993)

quality of life in rural areas depends on the rehabilitation of forests, which, in fact, is the principal aim of Joint Forest Management.

The potential of non-timber forest produces (NTFPs) for poverty alleviation is very important. The rural poor and tribal communities collect various kinds of products throughout the year to sustain their livelihood. Activities related to NTFPs provide employment during slack periods in the agricultural cycle and provide a buffer against risk and household emergencies. In fact, sustainable NTFP management is the key to the success of JFM.

In view of the philosophy of decentralized governance, people's involvement in decision-making process and consequent empowerment is crucial in such efforts. Village dynamics and social processes have to be understood properly. Sociological insight, perception and knowledge are, therefore, instrumental and essential for formulation, designing and implementing any effective approach to JFM which will lead to an integrated development of the rural poor. Sustainable forest management is the key to sustainable rural livelihood. There has to be a harmonious balance between the conservation of forests and the development of communities through livelihood security.

A sustainable alliance has to be forged among government, non-government and local-level organizations. There has to be an effective partnership among all the stakeholders for capacity building, monitoring and evaluation of JFM to achieve the ultimate goal of planning and development, i.e. self-reliance. It is clear that forest productivity will ensure equity and livelihood for the rural poor. The rural livelihoods must be integrated with development of forests, with the involvement of people in the form of village forest committee (VFC)/forest protection committee (FPC). Once they are involved, forest resource cycle (Fig. 7.10) will be completed.

7.7.1 Experiences of JFM in India

In the last two decades, the Joint Forest Management (JFM) has led to several positive impacts in India.

7.7.1.1 Rehabilitation and Improvement in the Conditions of Forests

There is evidence that JFM has rehabilitated degraded forests in India. In the past few years, the overall forest cover of the country has increased by 3896 km^2. One main reason for this rehabilitation and improvement is the successful implementation of the JFM. In areas under JFM, incidents of illicit felling have sharply declined. One of the more immediately visible ecological effects of JFM has been the recovery of fodder resources in JFM areas for stall-feeding. The prolific growth of understorey vegetation, in many instances, has led to increased biodiversity and relatively rapid increases in the wild herbivore population.

7.7.1.2 Increase in Livelihood Options

JFM programmes have created livelihood opportunities at several places, through sale of NTFPs, share from the final harvest of forest produces, income from ecotourism and share from it, etc. They are also allowed to collect medicinal plants from the forests free of cost and earn from it through selling. Further, JFM has helped many forest protection committees (FPCs) to build up a substantial level of community funds which are used for local development activities.

7.7.1.3 Reduction in Encroachments

At several places, JFM has helped to reduce the area under illegal encroachment and the rate of fresh encroachments. Joint Forest Management Committee (JFMC) members are helping the forest department to recover encroachment and subsequent afforestation. In Andhra Pradesh, nearly 12% of the encroached forestland has reportedly been vacated since the JFM programme was initiated.

7.7.1.4 Involvement of NGOs

The JFM programme has led to a considerable involvement of NGOs in the forestry sector although there is significant variation from state to state. This has facilitated interaction among communities and the government.

7.7.1.5 Change in Attitude and Relationship

One of the most significant impacts of the JFM programme has been the change in the attitude of local communities and forest officials towards each other and towards the mangrove forest. For instance, members of an FPC in Buldhana, Maharashtra, even postponed a wedding in their village in order to fight a forest fire. This was unthinkable in the pre-JFM days. The large number of training and orientation exercises carried out in the different states has also contributed to a positive change in attitude (Government of India 2002).

7.8 Conclusions

Income from mangrove forest products, agriculture and non-farm income are the major sources of income to the local people for maintaining their subsistence needs. However, the local people residing nearby the mangrove reserves depend much more on mangrove forests as they can access the mangrove forest products easily for generating their income. Income from mangrove forest products is the main source of their livelihood income and generates 43% of the total income of the household. So, households are significantly dependent on mangrove products.

The lower-level household income group had neither land for agriculture nor farm employment for generating their income, thereby increasing their dependency on the forest resources for subsistence. People are generating their livelihood income from the use of different mangrove resources like fish, crab, prawn and firewood. Firewood is a source of energy for cooking but some households collect firewood for commercial purposes. The second largest source of income is the farm income which accounts for 32% of the total livelihood and agricultural income shares 25% of household income. Lower- and middle-income-level households are more dependent on mangrove forest products as compared to high-income levels. Lower-income-level groups are generally landless and mostly dependant on mangrove forest products for their subsistence.

Mangrove forest resources are a major income contribution in the livelihoods of local communities, although a few households engage in other alternative livelihood activities, namely agriculture and non-farm employment. As mangroves provide an important contribution to local livelihoods issues on forest resource dependency and subsistence level of rural livelihood should not be ignored in policy-level decisions and other interventions. To reduce dependency on forest resources, avoid deforestation and inefficient utilization of forest resources the government needs to incorporate alternative income generation activities so that livelihood strategies can be diversified to sustain local livelihoods and implement forest rehabilitation activities for the protection, conservation and management of mangrove resources.

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Chapter 8
Climate Change and Mangroves

Daniel M. Alongi

Abstract Climate change impacts on mangroves have received considerable attention due to rising temperatures, sea level and greenhouse gas concentrations, changes in ocean circulation and precipitation patterns, and increasing extreme weather events. Mangrove responses depend on whether critical thresholds are reached. High temperatures and low precipitation lead to extreme warming events, driving increasing mangrove mortality. Sea-level rise (SLR) will be the prime driver of future mangrove change with a critical threshold of ~6 mm a^{-1}. Predicted rates are expected to exceed this threshold at intermediate (10 Gt CO_2 a^{-1}) to very high (~124 Gt CO_2 a^{-1}) emission scenarios. The Gulf of Mexico, northern Caribbean, East Asia, the Philippines, and eastern India are vulnerable due to increasing cyclones and storms, and Africa, Mexico, Pakistan, western India, and NW Australia are vulnerable due to high temperatures and increased aridity. Losses are expected on most oceanic islands, East Asia, Indonesia, Vietnam, India, Australia, and in river deltas due to low tidal ranges, subsidence, and lack of accommodation space. Mangroves may expand where rainfall will increase such as in Central America, SE Brazil, N and W South America, Malaysia, and Thailand. High rates of mangrove carbon sequestration may be a viable mitigation strategy, although mangrove carbon stocks and sequestration rates equate to only 1.6–2.6% of all other ecosystems. Only ~10% of mangrove carbon projects may be financially sustainable but would contribute ~30 $MtCO_{2eq}$ a^{-1} and yield an investment return of ~US \$3.7 billion a^{-1}, sufficient to meet many national climate mitigation goals.

Keywords Blue carbon · Climate change · Climate mitigation · Mangroves · Sea-level rise

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8.1 Introduction

Living at the intertidal edge between land and sea in the low latitudes, mangroves are subjected constantly to changes in environmental forces making them susceptible to climate change. The intertidal zone is highly dynamic physically, chemically, and geologically, with wide changes in wave action, tides, temperature, salinity, anoxia, and rainfall; it is mainly these forces that shape mangrove forests over time and space (Alongi 2009; Twilley and Day 2013).

Mangroves are thus highly adapted to a harsh, physically demanding environment, exhibiting a high degree of ecological stability and persistence in the face of environmental inconstancy. As such, they have a variety of ecosystem properties that serve to either facilitate and augment recovery from, or resilience to, disturbance including some that are unique, such as simple architecture, highly efficient but complex biotic controls, multiple morphological and physiological adaptations, especially to cope with salt and anoxia, and high ability to retain labile carbon, nutrients, and other elements (Alongi 2009; Twilley and Day 2013).

Much of the evidence for the high adaptability of mangroves to natural and human-induced disturbances comes from patterns of recovering forest stands that are reminiscent of pioneer-phase forests, as forest structure and composition develop from a complex interplay of physiological tolerances and competitive interactions that lead to a mosaic of 'arrested or interrupted' succession sequences, in response to changes in shoreline evolution and physiochemical gradients (Fromard et al. 1998; Alongi 2008). Some mangroves, however, either do not survive or are heavily impacted depending on the extent, severity, and duration of the disturbance.

Anthropogenic disturbance impacts on mangroves, including climate change, have received much attention of late due mainly to signs of increasingly severe changes in climate, such as rising temperatures and sea-level, changes in ocean circulation, rising atmospheric and marine greenhouse (GHG) concentrations, changes in precipitation patterns, and increasing frequency and severity of extreme weather events, such as drought and cyclones. Despite continued deforestation, mangroves still play important roles in the coastal zone in low latitudes where population growth is rapid, and poverty is endemic. Mangrove ecosystems are important both ecologically and economically, offering many ecosystem services such as ameliorating coastal erosion and the impacts of tsunamis and cyclones, and providing nursery and fishing grounds and breeding sites for many semiterrestrial, estuarine, and marine organisms, and serve as a reliable source of wood, food, and traditional medicines. They also play crucial biogeochemical and geochemical roles in the tropical coastal ocean.

This chapter will critically assess the impacts of climate change on mangrove forests and their associated waterways. The primary focus will be on sea-level rise, considering their intertidal nature, as well as rising levels of GHGs, temperatures, extreme weather events, and changes in rainfall patterns. Predictions will be offered based on analysis of the latest assessment of the Intergovernmental Panel on Climate Change (IPCC 2021). Finally, possible mitigation of climate change impacts will be discussed in light of recent work on carbon sequestration ('blue carbon') in these unique ecosystems.

8.2 Impacts of Climate Change

To realistically gauge future impacts, it is highly instructive to examine past and current episodes of climatic disturbances on mangroves. Such evidence offers insights into how mangroves respond to global environmental change.

8.2.1 Rising Temperatures, Increased Storms, Extreme Weather Events, and Precipitation Changes

During 2011–2020, the increase in global surface temperature (GST) since 1850–1900 was 1.09 (range: 0.95–1.20) °C with a further likely 1.5 °C increase during 2021–2040 and a very likely crossing of the 2 °C threshold during 2040–2060 period. Over the 2081–2100 period, average GST is very likely to be higher by 1.0–1.8 °C in the low CO_2 emission scenario and by 3.3–5.7 °C in the high emission scenario (IPCC 2021). By the year 2300, GST will be in the range of 0.9–9.6 °C higher depending in the rate of CO_2 emissions. Similarly, global mean sea surface temperatures (SST) have increased 0.88 °C (range: 0.68–1.01 °C) since 1900 and are projected to increase by 0.86 °C (0.43–1.47 °C) and by 2.89 °C (2.01–4.07 °C) by 2100 under low and high rates of CO_2 emissions, respectively (IPCC 2021). The tropical ocean has been warming faster than other regions since 1950 with fastest warming in parts of the Indian Ocean, western boundary currents, and the western Pacific Ocean due to a combination of local atmosphere-ocean coupling, the Indonesian Throughflow, and trends in the Walker circulation (IPCC 2021).

Mangroves show complex, but mostly positive, responses to increasing air and coastal ocean temperatures up to a critical threshold. Warmer temperatures affect mangroves by (1) altering species composition, (2) changing phenological patterns such as the timing of flowering and fruiting, (3) increasing plant productivity and canopy respiration where temperature does not exceed an upper threshold, and (4) expanding species ranges to higher latitudes where range is temperature-limited but not limited by other factors (Gilman et al. 2008; Jennerjahn et al. 2018). Rises in temperature may also result in (1) decreased survival in arid and increasingly arid zones, (2) increased water vapour deficit, (3) increased secondary production, and (4) shifts in species dominance and biodiversity (Alongi 2002, 2015). Rates of leaf photosynthesis peak for most species at or below 30 °C and leaf CO_2 assimilation rates of many species decline as temperatures increase from 33 °C to 35 °C (Alongi 2015).

Variations in air temperatures over long stretches of time have greatly influenced mangrove development. In Qinzhou Bay in tropical China, mangrove forests alternately flourished and deteriorated during warm and cold intervals, respectively, over the past ~3000 cal yr BP (calibrated years before the present) (Zhang et al. 2021). Mangroves expanded their development during the warm ~2220–1750 cal yr BP and ~1370–600 cal yr BP periods but deteriorated during the cold ~3000–2200 cal yr BP, ~1750–1350 cal yr BP, and the warming ~600 to 0 cal yr BP periods. Changes in relative sea-level, seawater temperature, salinity, and hydrodynamic conditions did not appear to have an impact on mangrove forest changes, but climate change, especially variation in air temperature, was the primary driver controlling mangrove development. Contrary to expectation, warming during the past 600 years has resulted in a decline in forest development, suggesting that the rise in air temperature during the Anthropocene has been too rapid to accommodate a positive mangrove response.

Latitudinal expansion of mangroves at the expense of salt marsh is underway (Cavanaugh et al. 2015; Whitt et al. 2020), encroaching in the Gulf of Mexico, Florida, New Zealand, Australia, southern China, and southern Africa, with air temperature and rainfall best explaining range expansion. This expansion and rising temperatures may impact the structure and function of mangrove flora and fauna by altering species' survivability, physiology, behaviour, and competitive abilities (da Silva Vianna et al. 2020).

While mangrove expansion appears to be driven primarily by increasing temperatures and reduced frequency of extreme cold events, changes in precipitation patterns and increasing frequency of storms cannot be ruled out as co-factors. Increased temperatures have affected the frequency and intensity of extreme weather events, such as droughts, storms, and cyclones. Direct impacts include increased erosion or smothering by sediment deposition and disturbance from intense wave action. Temperature anomalies, defined as extreme temperature events more than three standard deviations from the long-term mean (1951–1980), have shifted more than one standard deviation towards higher values, leading to more extreme warming events (Hansen et al. 2012).

The increased occurrence of such events is having a dramatic impact on mangroves, particularly more frequent episodes of mass mortality (Lovelock et al. 2017; Sippo et al. 2018, 2020; Duke et al. 2021; de Gomes et al. 2021; Zhu et al. 2021). The exemplar of such occurrences is the massive dieback of mangroves in the Gulf of Carpentaria, Australia (Duke et al. 2021), where 6–10% of the mangrove vegetation died back along 1000 km of shoreline during the summer of 2015–2016. The onset of the dieback was coincident with unprecedented high temperatures, low rainfall, and the lack of a normal monsoon. An unusually lengthy severe drought coupled with a temporary drop in sea-level associated with the 2015–2016 El Niño (Abhik et al. 2021) contributed to the mass mortality. Dieback conditions have severe consequences for ecosystem functioning as evidenced by a shift from a decline in oceanic carbon and alkalinity export (Sippo et al. 2020), loss of ecosystem carbon stock (de Gomes et al. 2021), and a weakening of GHG cycling with a lowering of both sink/source cycles in dry years (Zhu et al. 2021).

Recent large-scale mortality associated with extreme climatic events in Australia has accounted for 22% of all reported forest loss over the past six decades, suggesting the increasing importance of such extreme events (Sippo et al. 2018). In Mangrove Bay, Western Australia, there have been two dieback events over a 16-year period with the most recent one coincident with the dieback in the Gulf of Carpentaria; both dieback episodes on opposite sides of the continent coincided with periods of low sea-level due to intensification of ENSO leading to increased soil salinities and subsequent canopy loss and reduced recruitment (Lovelock et al. 2017). However, not all mangrove forests are significantly affected by extreme weather events, as found for Colombian mangroves in the Caribbean that appeared to be resilient to short ENSO-related drought events (Galeano et al. 2017). At the other extreme, some species such as *Avicennia germinans* may be resilient to extreme freeze events due to genetically based freeze tolerances (Hayes et al. 2020).

Rainfall patterns in the subtropics and tropics are changing, with weaker monsoons but more frequent and intense rainfall in parts of Africa, South Asia, and Southeast Asia (Alongi 2021). Higher rainfall ordinarily leads to more luxuriant and productive mangroves; rainfall-based thresholds have been identified for mangrove range limits in western North America, western Gulf of Mexico, western South America, Western Australia, the Middle East, north-west Africa, east-central Africa, and west-central Africa (Osland et al. 2017).

8.2.2 Sea-Level Rise (SLR)

Global mean sea level (GMSL) increased 0.2 (range: 0.15–0.25) m over the 1901–2018 period at a rate of 1.7 (range: 1.3–2.2) mm a^{-1} with an accelerated rate of 3.7 (range: 3.2–4.2) mm a^{-1} over 2006–2018, due to continued thermal expansion of the ocean and melting of glaciers and ice sheets (IPCC 2021).

Mangroves thrive at the ocean edge where they are naturally adapted to changes in sea-level over long timescales (Alongi 2002, 2015, 2021; Ward and de Lacerda 2021). The paleoenvironmental record indicates that over millennial timescales, mangroves have been exposed to different sea-level trajectories, suggesting a broad capacity to adjust to sea-level variations, as inorganic sediment supply, organic matter sequestration, and belowground root growth endow mangrove forests with considerable natural resilience in response to SLR (Woodroffe et al. 2016). Mangrove resistance and resilience to relative SLR over timescales of years to decades are the result of four main factors: (1) the rate of sea-level change relative to the mangrove soil surface, (2) species composition, (3) the physiographic setting, including the slope of the forest relative to that of the land the mangrove currently occupies, and (4) the presence of obstacles to landward migration (Gilman et al. 2008).

The ability of mangroves to adjust to rises in sea level depends on the sediment accretion rate relative to the rate of sea-level change, known as relative sea-level rise (RSLR). An analysis (Fig. 8.1) of mangrove accretion rates versus local mean SLR

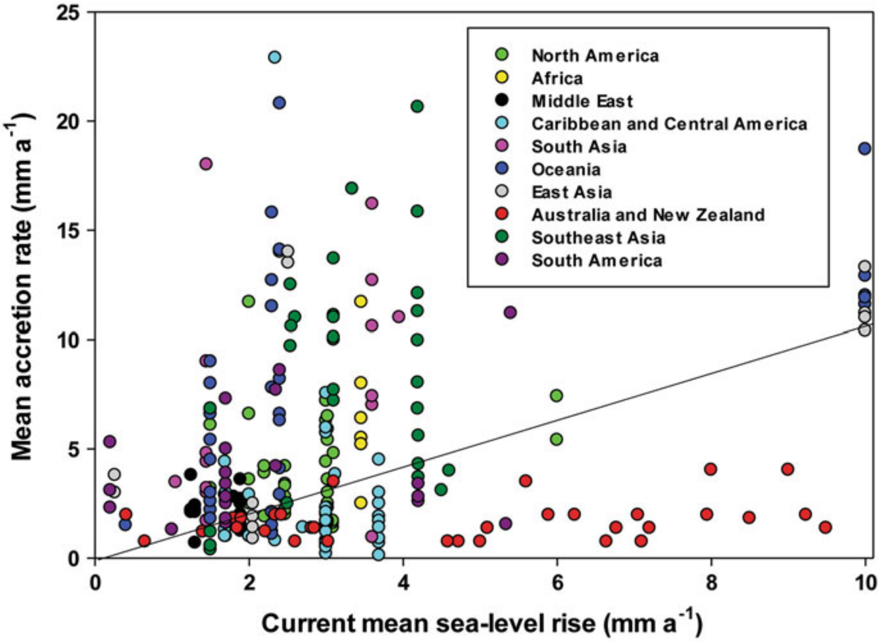

Fig. 8.1 The relationship between measured rates of mangrove soil accretion (mm a^{-1}) and current rates of mean sea-level rise (mm a^{-1}) worldwide. The sea-level rise data are from satellite altimetry or tide gauge data available from http://www.node.noaa.gov/General/sealevel.html. Mangrove sedimentation data are from references in Fig. 9.1 caption in Alongi (2021). The solid line delimits a 1:1 relationship between mean accretion rate and rate of sea-level rise (reproduced with permission from Alongi 2021)

indicates that mangroves located in the following locations (i.e. data points below the solid line in Fig. 8.1) are not keeping pace with RSLR: Australia, New Zealand, the Caribbean, Central America, on some, but not all (Esteban et al. 2019) low coral islands, and in subsiding river deltas such as the Sundarbans and in Southeast Asia. In contrast, mangroves (i.e. data points above the solid line in Fig. 8.1) located in other parts of Southeast Asia and the Pacific (e.g. New Guinea), South America, Africa, the Middle East, South Asia, and East Asia are keeping pace with current SLR as many of these forests occur in areas of rapid accretion due to highly impacted and populated catchments, especially in China, Brazil, and India.

However, the wide scatter of data points reflects how mangroves in disparate coastal settings in different parts of the world respond very differently to the same rate of SLR. This variability is also because some of the methods used to measure surface accretion (e.g. radionuclides) have considerable uncertainty; accretion rates do not reflect changes in surface elevation gain as a forest may be rapidly accumulating soil, but the local area may be subsiding, resulting in a net decrease relative to sea-level as is currently happening in many tropical river deltas (e.g. Sundarbans, Mekong). An analysis of recent trends in mangrove surface elevation changes across

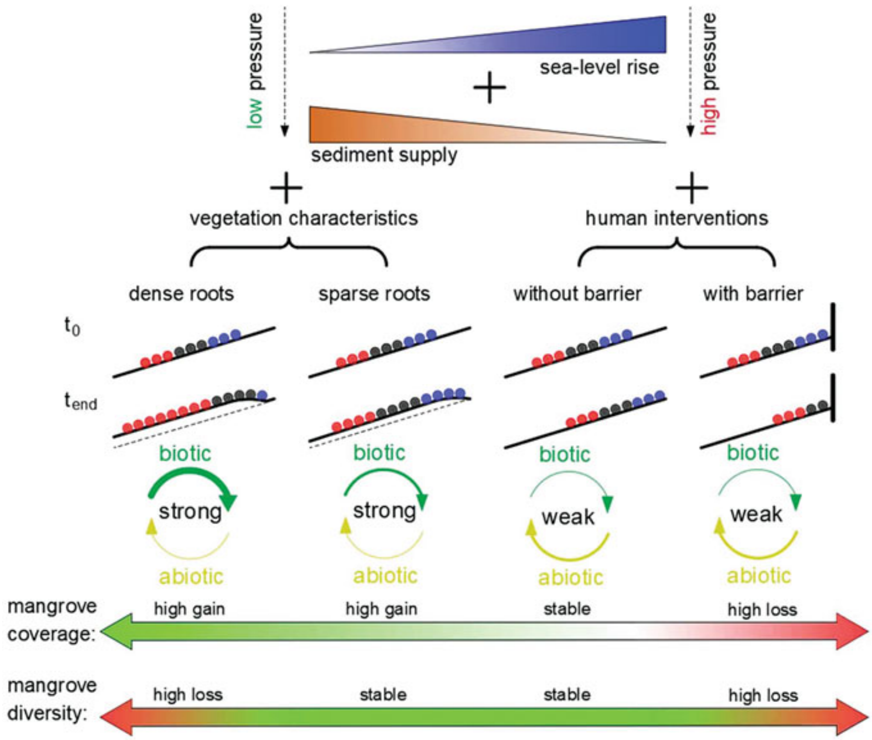

Fig. 8.2 Model results showing the complexity of mangrove response under different sea-level rise and sediment supply conditions. Under low environmental pressures, profile and vegetation distribution changes are determined by vegetation characteristics, while possible responses under high environmental pressures are mainly impacted by the presence or absence of anthropogenic barriers. The role of bio-morphodynamic feedback is indicated i.e., 'strong' versus 'weak', and arrow thickness represents the relative strengths of biotic and abiotic interactions (reproduced from Xie et al. 2020. Licensed under CC BY 4.0)

the Indo-Pacific region shows that for 69% of mangroves the current rates of SLR exceed soil surface elevation (Lovelock et al. 2015).

Mangrove responses to RSLR are complex, with clear species-specific differences in response to waterlogging and SLR (Cardona-Olarte et al. 2006; Chen and Wang 2017). For instance, the cosmopolitan species *Avicennia marina* and *Rhizophora stylosa* are highly tolerant to waterlogging, but their responses vary with immersion depth and time, salinity, and temperature (Mangora et al. 2014; Chen and Wang 2017).

A modelling study (Xie et al. 2020) has demonstrated the complexity of mangrove responses to RSLR (Fig. 8.2), illustrating the importance of the interaction between mangroves and hydrologic-sedimentary processes, both in the absence and in the presence of anthropogenic barriers impeding inland migration. Mangrove area can increase despite SLR if sediment supply is sufficient and landward accommodation space is available (Fig. 8.2), but tidal barriers are detrimental to mangrove survival and may result in species loss. Bio-morphological feedback may cause spatial and temporal variations in sediment delivery across the forest and reduced deposition despite longer inundation (Xie et al. 2020). Such feedback may decouple accretion rate from inundation time, altering habitat conditions and causing loss of biodiversity even when forest coverage remains stable or is increasing. Further, the model indicates that vegetation-induced flow resistance linked to root density may be a major factor steering the inundation-accretion decoupling and thus species distribution. Therefore, mangroves show considerable resilience to fluctuations in relative sea-level due to their ability to actively modify their environment through surface elevation changes (Ward and de Lacerda 2021) and their ability to migrate inland over time (Krauss et al. 2014).

Positive surface elevation change is facilitated by deposition of organic matter as well as by subsurface compaction and trapping and retention of inorganic sediments (Krauss et al. 2014; McKee et al. 2021). Thus, forest survival is likely driven not only by local rates of SLR, but also by sediment availability, autochthonous peat production, land uplift/subsidence rates and localized sediment auto-compaction. Fringe mangroves are on average most susceptible to SLR, but high tree densities can facilitate surface accretion, surface elevation change, and tree survival in areas most susceptible to SLR (Kumara et al. 2010; McKee et al. 2021; Ward and de Lacerda 2021).

The effect of SLR on the landward migration of mangroves is highly site-specific: while seaward mangroves may be most susceptible to drowning and loss, there may be landward migration if there is available space. This process can be helped by oceanographic anomalies (Lopez-Medellin et al. 2011). For example, on the Pacific coast of Mexico, a significant increase in mangrove area has occurred in the lagoons of Magdalena Bay in Baja California during the past four decades, especially during the El Niño anomalies of the 1980s and 1990s, while at the same time the mangrove fringe was receding. The observed change was attributed to the combined action of the warmer waters of the El Niño events and SLR. These two processes were sufficient to flood large areas of tidal salt flats dispersing mangrove seedlings inland.

8.2.3 *Rising Atmospheric CO_2*

Over the past 50 years, mean atmospheric CO_2 concentrations have increased from 326 ppm to 416 ppm and are still rising (IPCC 2021). Elevated atmospheric CO_2 concentrations enhance photosynthesis, growth, and leaf chlorophyll concentrations in most mangroves, with responses being species-specific and variable, depending on salinity, temperature, nutrient availability, and water-use efficiency (Reef et al. 2016; Tamimia et al. 2019; Manea et al. 2020; Maurer et al. 2020; Jacotot et al. 2021). The response of mangroves to increasing CO_2 concentrations is, however, complex due to interactive effects of elevated CO_2 with various other drivers, such as temperature and salinity (see early references in Alongi 2002, 2015). For example, transpiration efficiency of the species *Rhizophora mangle*, *Avicennia germinans*, *Conocarpus erectus*, and *Lumnitzera racemosa* increased with increasing CO_2 concentrations, but only at low salinity (Alongi 2015).

Most mangrove species will respond positively to increasing CO_2 levels, but some species will respond negatively or will exhibit no or little change. In greenhouse experiments, growth of *A. germinans* seedlings was enhanced only under elevated CO_2 and high nutrient conditions, but root growth doubled under low nutrient and elevated CO_2 conditions (Reef et al. 2016). Under similar experimental conditions, *A. germinans* seedlings exhibited increased salt tolerance and high photosynthetic rates under increasing, ambient, and high CO_2 levels and with a dose of the osmolyte, glycine betaine, which increases tolerance to environmental stress (Maurer et al. 2020). Other species also exhibit complex outcomes when subjected to elevated CO_2 concentrations with different amounts or rates of other physicochemical factors. For example, when subjected to ambient CO_2 and a temperature of 38 °C, *Rhizophora apiculata* seedlings responded positively to the high temperature but elevated CO_2 enhanced growth only at a lower temperature; under high temperature and elevated CO_2, the seedlings nearly died (Tamimia et al. 2019).

Thus, mangrove species show variable outcomes to elevated CO_2 when subjected to other drivers such as increasing temperatures and tidal inundation. Confounding responses have been observed in other species such as *A. marina*, *R. stylosa*, *Kandelia obovata*, and *Aegiceras corniculatum* (Jacotot et al. 2018; Yin et al. 2018; Manea et al. 2020). Net photosynthetic rates and water-use efficiency of *A. marina* and *R. stylosa* increased when grown under elevated (800 ppm) CO_2 levels and increasing tidal flooding to simulate sea-level rise (Jacotot et al. 2018), but these gains were minimal under longer flooding conditions. Such complex responses may offer a competitive advantage when mangroves encroach upon salt marshes. Growth of a model salt marsh community with *A. corniculatum* and *A. marina* under increasing CO_2 and low salinity resulted in the mangroves outcompeting the salt marsh species and with *A. marina* producing 48% more biomass under elevated CO_2 (Manea et al. 2020). In contrast, *A. corniculatum* was unaffected by higher CO_2, but had 36% greater growth than marsh plants when grown under full seawater.

Increased CO_2 can result in changes in the root microbiome (Yin et al. 2018). Over a period of 20 weeks with elevated CO_2, leaf chlorophyll levels in *K. obovata* increased as did microbial root biomass, with a shift in composition of ammonia-oxidizing archaea. There was also a shift in carbon utilization from sugars, amino acids, and carboxylic acids under ambient conditions to use of additional substrates in the following order: amino acids > carbohydrates > polymers > carboxylic acids > amines > phenolic acids, indicating a change in carbon metabolism.

8.2.4 Coastal Acidification

Open ocean pH has declined since preindustrial times by about 0.1 unit due to uptake of atmospheric carbon released from fossil fuel combustion, cement production, and land-use change (IPCC 2021). The subsequent hydrolysis of increasing CO_2 in seawater increases the hydrogen ion concentration thereby reducing pH and altering seawater carbonate chemistry. In tropical and subtropical coastal waters, however, pH is lower than in the open ocean and much more variable.

Nearly all tropical estuarine and nearshore waters, including mangrove tidal creeks and waterways, naturally exhibit very wide variations (see Table 4 in Alongi 2020a) in pH (range: 4.4–9.5), salinity (range: 0–47.4 psu), and carbonate chemical parameters, especially pCO_2 (range: 4–32,763 μatm). Tropical estuarine and coastal waters are in fact a strong source of CO_2 emissions to the atmosphere due to pCO_2 and $[CO_3^{2-}]$ oversaturation. Oversaturation and highly variable pH are the net result of high rates of mostly microbial respiration, eutrophication, and fluvial discharge, including export of alkalinity, organic matter, and CO_2, deposition of anthropogenic acids and bases, intense weathering, land-use change, acid sulphate soil discharge, and acidic groundwater (Duarte et al. 2013). Regulation of estuarine and coastal pH is therefore more complex than in the open ocean.

Mangroves are likely to be very resilient to coastal acidification considering the highly variable physiochemistry of tidal waters (Alongi 2020a) and the ordinarily low pH of mangrove soil (range: 4–7) as interstitial water is usually acidic due to root excretion of organic acids such as polyphenolic acids (tannins) and microbial decomposition of organic matter (Alongi 2009). Subsurface transport of groundwater derived from acidic soil waters also plays a major role in maintaining acidic conditions (Sippo et al. 2016).

Some mangrove ecosystems are apparent buffers of acidification in the tropical coastal zone due to net export of alkalinity (Sippo et al. 2016; Maher et al. 2018; Call et al. 2019; Reithmaier et al. 2020; Cabral et al. 2021; Saderne et al. 2021). In six Australian mangrove creeks, alkalinity fluxes ranged from an import of 1.2 mmol m^{-2} d^{-1} to an export of 117 mmol m^{-2} d^{-1} with a mean export of DIC (Sippo et al. 2016). Upscaling globally, mangrove alkalinity exports equate to 4.2 Tmol a^{-1}, equivalent to about 14% of global river or continental shelf benthic alkalinity fluxes. Export of large amounts of DIC and alkalinity increases coastal ocean pH, partly counteracting coastal acidification, so mangroves may thus be one of the largest sources of alkalinity to the tropical coastal ocean, helping to buffer acidification.

The ability of mangroves to buffer acidification, however, likely depends on geomorphological setting. For instance, in a semi-enclosed lagoon surrounded by a 25-m-wide fringe of *R. mangle* in southwestern Puerto Rico (García-Troche et al. 2021), biweekly sampling over 2 years measured pCO_2 and DIC/TA ratios ranging from 497 to 845 μatm (mean = 674) and 0.882–0.904 (mean = 0.896). These values imply heterotrophy was the main driver for persistent acidification, which was maximal during the wet season, indicating that mangrove lagoons with limited water exchange and high carbon input will not ameliorate acidification.

8.2.5 Increasing Hypoxia

The expansion of oxygen minimum layers and dead zones illustrates the global decline in dissolved oxygen (DO) concentrations in the ocean since the mid-twentieth century, and the subsequent change in geographic and vertical ranges of marine organisms in the last 20 years (IPCC 2021). DO concentrations are declining fastest in the tropical latitudes where higher temperatures decrease the saturation capacity of DO in seawater while simultaneously increasing rates of microbial respiration that consumes and depletes DO. Deoxygenation is driven by increasing SSTs and eutrophication and is likely widespread in tropical ecosystems such as coral reefs, seagrass beds, and mangrove forests (Altieri et al. 2019).

Mangroves are naturally subject to hypoxia for intermittent spatial and temporal periods with the main drivers being: (1) physical features, such as ponds and channels, that reduce O_2 replenishment by increasing stratification and reducing tidal flushing, all enhanced by tides, seasonality, and extreme weather, (2) their complexity and high organic matter production result in the trapping of organic material which fuels decomposition and subsequent O_2 depletion, and (3) naturally rapid rates of O_2 consumption can lead to a decline in DO which can be exacerbated by the dampening of water flow by the forest (Altieri et al. 2021).

Mangroves have several mechanisms to cope with and mediate low DO levels and can to a considerable extent, counteract hypoxia. They possess structural and physiological attributes such as aboveground roots that supply oxygen to the remainder of the tree and can utilize oxygen stored in their tissues, create oxygenated microhabitats, absorb oxygen from the atmosphere and/or redistribute oxygen internally to counter low-oxygen conditions (Altieri et al. 2021). In addition, several trophic groups have high tolerances to hypoxia, including fish, molluscs, and a variety of benthic and planktonic invertebrates. Some of these tolerances are facilitated by mutualistic relationships with other organisms, including the trees. Diel cycling of DO occurs naturally in tidal mangrove waters, with a wide range of values (range: <1 to >8 mg l^{-1}; Altieri et al. 2021) mimicking the wide range of other physicochemical parameters such as pH, salinity, and pCO_2. This variability is the net result of tidal changes in temperature, high respiration rates, eutrophication, fluvial discharge, tidal exchange of alkalinity, organic matter and CO_2, deposition of anthropogenic acids and bases, intense weathering, land-use change, acid sulphate soil discharge, and acidic groundwater (Alongi 2020a).

8.3 Predictions

The latest IPCC assessment (IPCC 2021) makes the following climate change predictions:

- Compared with 1850–1900, mean global air temperature over the 2021–2040 period is very likely to increase a further 1.5 °C with the 2 °C warming level very likely to be crossed during the 2041–2060 period. Average global air temperature over the 2081–2100 period is very likely to be higher by 1.0–1.8 °C in the low CO_2 emissions scenario (‘SSP1-1.9’) and by 3.3–5.7 °C in the high emission scenario (‘SSP5-8.5’). Global air temperatures are likely to range from 0.9 °C to 9.6 °C higher by 2300 depending on the emissions scenario.
- Marine heatwaves will likely increase by two to nine times in 2081–2100 than currently under ‘SSP1-1.9’ and 3–15 times more frequently under ‘SSP5-8.5’ with the largest changes in the tropical ocean. The amount of ocean warming since 1971 will likely at least double by 2100 under a low emissions scenario and will increase four to eight times under a scenario of high CO_2 emissions and will likely continue to increase until at least 2300, even for the low emissions scenario.
- SSTs are projected to increase 0.86 (range: 0.43–1.47) °C and by 2.89 (range: 2.01–4.07) °C by 2100 under low and high CO_2 emission scenarios, respectively.
- High salinity regions will become saltier, and low salinity areas will become less salty, with large-scale patterns growing in amplitude over this century.
- Ocean currents will change in the twenty-first century in response to changes in wind stress. The Indonesian Throughflow and all four eastern boundary upwelling systems are projected to weaken in low latitudes.
- Precipitation will very likely increase over the tropical ocean and likely increase in large parts of the monsoon regions but will likely decrease in the subtropics. ENSO-associated rainfall variability will increase significantly by 2050–2100. Frequency and intensity of rainfall will continue to increase across Asia.
- Ocean pH will likely decrease -0.38 ± 0.005 under a high emissions scenario by 2081–2100, with increased temporal and spatial variability in the coastal ocean. pH will be lower in tropical coastal waters due to increased eutrophication and respiration due to higher temperatures.
- More severe hypoxia or anoxia is predicted in highly populated coastal areas.
- South and Southeast Asian monsoonal circulations will weaken with a decreasing trend of monsoon frequency over the Bay of Bengal resulting in increasing breaks or dry spells.
- The East Asian monsoon will get stronger due to SST changes in the Pacific with increased rainfall.
- The West African monsoon will continue to recover from the very dry period (1970s to 1990s) with more extreme events with an increase in rainfall in east and central Africa and a decrease in west Africa with a delayed wet season.
- Increase in frequency and intensity of extreme weather events such as cyclones and drought.

- Onset of the South American monsoon season will continue to be delayed.
- Rainfall extremes during the Australasian and maritime monsoons have increased since the 1970s with prediction of increased rainfall over Indonesia.
- River floods are projected to increase in humid west Africa, especially in the deltas of the Niger, Volta, and Gambia Rivers.
- There is medium confidence that rainfall will decrease in Central America and in small islands in the western Indian Ocean, western Tropical Pacific, and Caribbean.

Logically, under a high CO_2 emissions scenario, mangroves in future will not fare as well as under a low emissions scenario, although any predictions must be tempered with caution due to the considerable uncertainties in many of the models used. However, mangroves will almost certainly decline under the following conditions: (1) at air and sea surface temperatures at or above the forecasted increase of >3.3 °C and 2.89 °C, respectively, which are above critical thresholds, (2) under greater and more frequent marine heatwaves whereby dieback events would increase, (3) changes in ocean currents such as a decrease in the Indonesian Throughflow may result in a weakening of mangrove propagule dispersal lessening the chance of mangrove survival and recruitment in more favourable habitats, (4) increased rainfall will facilitate mangrove growth and vice versa in areas of predicted drought/dryness/increased salinity, (5) more frequent and intense hypoxia will affect some mangrove-associated biota such as nekton, plankton, and benthos, and (6) in areas where monsoons are expected to weaken mangroves will likely decline in area, biodiversity, and change in species composition and dominance, and vice versa in areas of stronger monsoons. Increased cyclones can offer some benefits (increased rainfall) but stronger cyclones (higher winds) will result in greater damage. Of course, as found from experimental studies, results are likely to be complex once interactive effects are considered such as the confounding effects on mangrove growth of higher CO_2 concentrations, higher temperatures, and lower salinity (Alongi 2002).

Negative responses by mangroves will lead to other effects, as the loss of forest area will lead to decreases in ecosystem services, including cultural functions (Jennerjahn et al. 2018). Any shift in community composition will likely lead to changes in provisioning services such as fisheries outputs, including aquaculture, fuelwood, building materials, and traditional medicines. Regulating ecosystem services will likely also change. For instance, coastal protection from cyclones, tsunamis, waves, and floods will inevitably decline due to loss of mangroves related to rapid RSLR, reduced freshwater inflow, and increasing intensity of storms. Water quality maintenance will probably decline/increase and decrease/increase with increased freshwater flow and altered tidal hydrology. Increased/reduced allochthonous sediment input related to increased/decreased freshwater input may increase/decrease protection of the coastline, beach erosion, land stabilization, and climate regulation; nutrient cycling, biodiversity and nursery functions will also be altered.

Table 8.1 Predicted rates of sea-level rise (mm a^{-1}) under (a) five CO_2 emission scenarios[a] and (b) five different temperature rise scenarios during the 2040–2060 and 2080–2100 periods (IPCC 2021). Values are forecasted medians, and ranges are in parentheses. Green values indicate probable mangrove survival, yellow values indicate possible survival and red values indicate probable mangrove drowning.

Rate of sea-level rise (mm a^{-1})	(a) CO_2 emissions scenarios[a]				
	Very low	Low	Intermediate	High	Very high
2040–2060	4.2 (2.9–6.1)	4.9 (3.6–6.9)	5.9 (4.5–8.0)	6.5 (5.1–8.7)	7.3 (5.7–9.8)
2080–2100	4.3 (2.5–6.6)	5.3 (3.3–8.1)	7.8 (5.3–11.5)	10.4 (7.5–14.9)	12.2 (8.8–17.7)
Rate of sea-level rise (mm a^{-1})	(b) Global surface air temperature scenarios				
	1.5 °C	2.0 °C	3.0 °C	4.0 °C	5.0 °C
2040–2060	4.1 (3.0–5.8)	5.1 (3.8–7.1)	6.0 (4.7–8.2)	6.5 (5.1–8.6)	7.3 (5.8–9.8)
2080–2100	4.3 (2.6–6.5)	5.5 (3.5–8.3)	7.9 (5.4–11.6)	9.9 (7.2–14.2)	11.8 (8.6–17.0)

[a] Current CO_2 emissions are 40 Gt CO_2 a^{-1} compared with the very low (−15 Gt CO_2 a^{-1}), low (−10 Gt CO_2 a^{-1}), intermediate (10 Gt CO_2 a^{-1}), high (≈82 Gt CO_2 a^{-1}), and very high (≈124 Gt CO_2 a^{-1}) model emissions scenarios

Arguably, sea-level rise is likely to be the prime driver of mangrove response in future. Although palaeorecords indicate that mangroves are resilient to increasing sea-level over historical timescales (Ellison 2000; Alongi 2015), current and predicted rates of SLR are rapid in comparison, likely too rapid to facilitate mangrove adjustment and encroachment landwards. Mangroves expanded between 9800 and 7500 years ago at a rate driven mainly by the rate of relative SLR, but it was highly likely (90% probability) that they were unable to sustain accretion when relative SLR exceeded 6.1 mm a^{-1} (Saintilan et al. 2020). This finding agrees with the data in Fig. 8.1 that rates of SLR greater than 6 mm a^{-1} represent a critical threshold for submergence. Mangrove forests are likely 'losers' with respect to RSLR in regions where there is substantial subsidence, such as in river deltas and on islands, such as the Sundarbans and the Solomons, respectively (Albert et al. 2018), a low tidal range, changes in precipitation, and/or declining ecological conditions (Cinco-Castro and Herrera-Silveira 2020). The reality is that, as they have in the past, mangroves will respond in complex ways to future SLR. If the rate of SLR is slow enough ($\leq$ ~6 mm a^{-1}), some forests will likely survive although there will probably be significant changes in forest structure and species

Table 8.2 Predicted mangrove responses to forecasted climate change by 2100 based on IPCC (2021) climatological criteria and ecological criteria (Alongi 2008, 2015, 2021; Lovelock et al. 2015; Jennerjahn et al. 2018; Saintilan et al. 2020)

Region	Prediction
Southern United States	Increase in damage/destruction from increasingly frequent and stronger hurricanes. Latitudinal expansion continues.
Africa	Continued poleward expansion in S. Africa. High risk of losses due to deforestation/degradation as most mangroves highly fragmented. Losses from high heat and aridity in NW and SE Africa.
Middle East	Losses due to increasing aridity, especially in Red Sea. Landward expansion/migration unlikely.
Caribbean/Central America	Increasing ENSO rainfall likely to increase sediment delivery along S. Caribbean coast of Central America. Decline in Mexican mangroves (both coasts) due to increasing aridity.
South America	SE Brazilian mangroves likely to increase due to increased temperatures. N. South American mangroves unlikely to be impacted due to increased rainfall and sediment supply. Pacific coast mangroves likely to continue increasing in size but no poleward expansion due to cold currents and arid conditions.
South Asia	Arid-zone mangroves likely to decline in Indus delta due to low rainfall, subsidence, and low sediment delivery. E. India vulnerable to low tidal range, subsidence, and increased cyclone activity.
Southeast Asia	Philippines, Indonesia, and Vietnam vulnerable to SLR due to low tidal range. River delta mangroves likely to decline with SLR, subsidence, and decreased sediment supply.
East Asia	S. China mangroves vulnerable to SLR due to lack of upland space for migration and increased typhoon activity.
Pacific Islands	Islands of Oceania highly vulnerable to SLR due to lack of upland space for landward migration.
Australia/New Zealand	Mangroves in NW Australia likely to decline due to increasing aridity. SE Queensland and SE Australia mangroves not keeping pace with SLR. New Zealand mangroves likely to expand on north island as temperatures increase.

composition, morphology, and anatomy, including changes in fibre wall thickness, bark anatomy, changes in vascular vessel densities, formation of hypertrophied lenticels and adventitious roots, and increased aerenchyma development (Alongi 2015). At higher rates of SLR ($\geq \sim 6$ mm a^{-1}), mangroves will only survive if there is sufficient land space higher up on shore to accommodate forest establishment (Table 8.1).

Regional vulnerability will depend on other drivers in addition to SLR including temperature, aridity, salinity, storm and cyclone frequency and intensity, and coastal setting. For instance, mangroves situated in river- and tide-dominated settings would best be able to cope with climate change as allochthonous materials from land and sea will enable sediment accretion to keep pace with rising seas; these areas would include macrotidal estuaries and wet tropical coastal regions (Jennerjahn et al. 2018; McKee et al. 2021).

Based on these criteria, several studies (Alongi 2008, 2015, 2021; Lovelock et al. 2015; Jennerjahn et al. 2018; Saintilan et al. 2020) have identified regions most vulnerable to climate change (Table 8.2). Increasing frequency and intensity of hurricanes, cyclones, and typhoons will negatively impact the Gulf of Mexico, northern Caribbean, East Asia, The Philippines, and eastern India whereas high temperatures and increased aridity will cause losses in northwest and southeast Africa, Mexico, Pakistan, western India, the Middle East, and northwest Australia (Table 8.2). Due to a combination of low tidal ranges, subsidence, and lack of accommodation space, mangrove losses will occur on most Pacific Ocean, Indian Ocean and Caribbean Sea Islands, East Asia, east coast of Sumatra, north coast of Java, Sulawesi, southern Vietnam, eastern India, northeast and southeast Australia, and in many river deltas, such as in the Sundarbans, Mekong, Ayeyarwaddy, and Niger Rivers. A few areas are especially vulnerable and are currently experiencing mangrove drowning, including low coral islands in the Indo-West Pacific and the Caribbean. A major co-factor facilitating mangrove loss is erosion, agriculture/aquaculture and degradation and deforestation coupled with a high degree of fragmentation, such as in Africa and Asia (Bryan-Brown et al. 2020).

Some forest expansion and little or no responses by mangroves are forecast in regions where rainfall will increase, such as along the south Caribbean and Pacific coasts of Central America (e.g. Costa Rica), in southeast Brazil, along the western and northern coasts of South America, west coast of Peninsular Malaysia, and the southwest coast of Thailand. Latitudinal expansion will continue along the Gulf of Mexico coast of the United States, both coasts of Florida, SE and E Australia, New Zealand, southern Africa.

8.4 Climate Change Mitigation

8.4.1 Significance of Mangrove Blue Carbon

"Blue carbon," defined as the carbon sequestered and stored by coastal ocean ecosystems, including mangroves (Fig. 8.3), has been increasingly used conceptually to document the carbon management potential of these ecosystems to protect and, if necessary, to restore them to maintain and expand their ability as critical carbon sinks to assist in reducing GHG emissions (Alongi 2018). When these coastal habitats are destroyed, their carbon is released back into the atmosphere, thus reversing the effect of fostering carbon sequestration in REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and other rehabilitation projects (IOC 2011; Sifleet et al. 2011; Herr et al. 2012).

There are three components of carbon sequestration in mangroves: (1) the annual sequestration rate, that is, the annual flux of organic carbon (C_{ORG}) transferred to anaerobic soils and sediments where it cannot undergo oxidation to CO_2 to be returned to the atmosphere, (2) the amount of carbon stored in above- and belowground biomass, and (3) the total ecosystem C stock stored belowground as a result

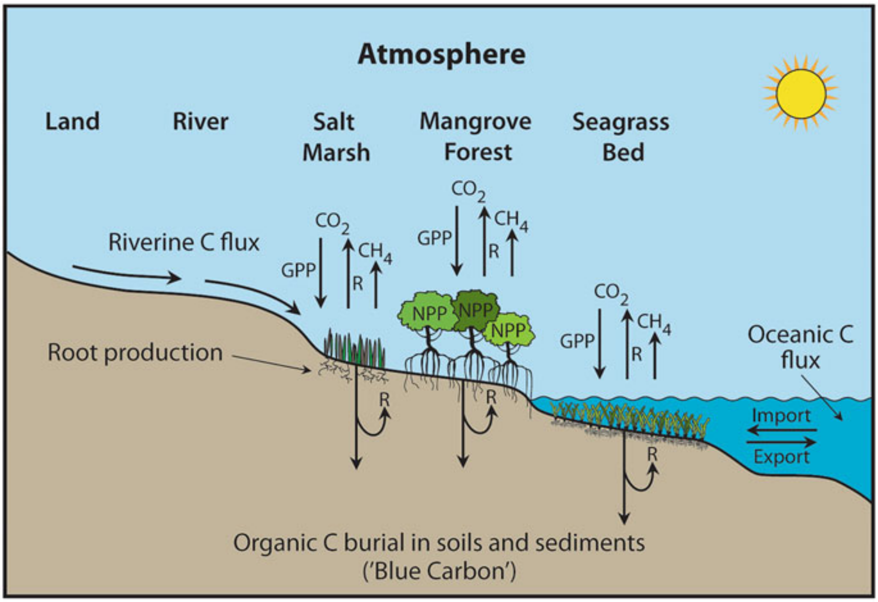

Fig 8.3 Conceptual model of blue carbon in coastal ecosystems. *GPP* gross primary production, *NPP* net primary production, *R* respiration, CO_2 carbon dioxide, CH_4 methane (reproduced with permission from Alongi 2018)

of prior sequestration, that is, historical sequestration over a given habitat's lifetime. There has been impressive growth in mangrove blue carbon papers reflecting the need of NGOs and various agencies for more data, as well as a lot of enthusiasm for the idea that blue carbon storage and sequestration are of great significance in reducing carbon emissions to ameliorate the effects of climate change.

The destruction of mangrove forests, especially if the soil horizon is removed or disturbed, can result in significant carbon losses (Pendleton et al. 2012; Huxham et al. 2018), especially if converted to aquaculture ponds, cattle pastures, and infrastructure upon deforestation, to the extent that more than 50% of mangrove carbon has been lost and returned to the atmosphere. Immediate removal of biomass and soil results in extremely high losses (see Table 2, Alongi 2020b) with CO_{2eq} emissions averaging 1802.2 Mg ha^{-1} a^{-1} and ranging from 407.0 to 2781.5 Mg ha^{-1} a^{-1} as estimated for mangroves in Brazil, Mexico, the Philippines, Honduras, Dominican Republic, Indonesia, and Costa Rica. Most emissions are derived from loss of soils to a depth of 1 m, so if soils deeper than 1 m are dredged, the estimated $CO_{2\ eq}$ flux to the atmosphere will be much greater. Assuming total deforestation of mangroves (biomass + soils to 1 m depth) and using the mean CO_{2eq} emission of 1802.2 $MgCO_{2eq}$ ha^{-1} a^{-1} and multiplying by an annual average deforestation rate of 0.16% (Hamilton and Casey 2016; Hamilton and Friess 2018) and the low and high estimates of global mangrove area of 83,495 km^2 (Hamilton and Casey 2016) and 137,760 km^2 (Giri et al. 2011), we estimate annual losses of

Table 8.3 Estimated global mean C stocks, C sequestration rates and CO_2 emissions due to losses from mangrove forests, salt marshes, seagrass meadows, coral reefs, the tropical coastal ocean, and terrestrial ecosystems. Table is derived from Table 3 in Alongi (2020b)

Ecosystem	Global mean C stock (Pg C_{org})	Global C sequestration (Tg C_{org} a^{-1})	Current conversion rate (% a^{-1})	Carbon emissions (Pg CO_{2eq} a^{-1})
Mangrove	6.17–9.99	14.98–24.27	0.16	0.088–0.14[a] (0.036–0.058)
Salt Marsh	1.74	11.66	1.32	0.084
Seagrass	2.61	35.31	1.5	0.144
Coral Reef	0.03	3.0	0.43	0.0005
Tropical coastal ocean	36.0	3.9	0.93	0.5
Tropical forest	553.0	1100.0	0.53	10.8
Temperate forest	292.1	300.0	0.70	7.5
Boreal forest	395.0	246.6	0.80	11.6
Tropical grass-land/savanna	455.4	315.0	0.70	11.7
Temperate grassland	226.4	210.0	0.55	4.6
Desert and xeric shrub land	119.7	432.3	0.3	1.3
Montane grasslands/ forests	90.3	ND	0.49	1.6
Mediterranean forest	87.4	212.8	ND	ND
Tundra	1486.0	528.0	ND	ND
Boreal peatlands	427.0	191.7	ND	0.26
Tropical peatlands	119.2	31.8	ND	1.48

[a] Estimated assuming total forest biomass and soil losses to a depth of 1 m and low and high area estimates as discussed in text. CO_2 emissions based on global sequestration rate are in parentheses

between 24.08 and 39.7 $TgCO_{2eq}$ a^{-1} or 0.0024 and 0.0039 $PgCO_{2eq}$ a^{-1}, respectively.

Are mangrove blue C stocks and C sequestration rates globally significant? The global mean C stock for mangroves is the largest of any ecosystem in the global tropical ocean (Table 8.3). Although mean mangrove C stocks per unit area are the largest among the world's ecosystems (except tundra and peatlands), global mangrove C stocks equate to only 1.6–2.6% of individual terrestrial ecosystem global C stocks (Table 8.3). Regarding C sequestration among coastal environments, seagrass meadows sequester slightly more than one-third to twice the amount mangroves store. Mangroves sequester ~50–76% of tropical peatlands globally but only 4%

compared to other terrestrial ecosystems (range: 1.3–8%). CO_2 emissions due to deforestation and other destructive land-use practices result in large returns of CO_2 to the atmosphere, for a total of ~51.7 Pg CO_{2eq} a^{-1} (Table 3 in Alongi 2020b). Assuming that all mangroves are destroyed at a rate of 0.16% a^{-1}, total CO_2 emissions can range from 0.088 to 0.142 Pg CO_{2eq} a^{-1} depending on total mangrove area. This range equates to 0.17–0.27% of total estimated global carbon emissions.

While there is no doubt that mangroves store and sequester large amounts of carbon relative to their small global area, they play only a minor global role in storing C_{org} and in mitigating CO_2 emissions. Mangrove CO_2 emissions are, however, significant throughout the tropical coastal ocean, accounting for about 18–28% of CO_2 emissions from the tropics (seagrasses account for 29% and coral reefs 0.1% of tropical coastal ocean emissions; the remaining 52.9% is accounted for by nearshore coastal waters and subtidal benthos). It must be noted that these C stock and C rate estimates are crude and can only point to relative differences, as there are significant data limitations. Taillardat et al. (2018) similarly estimated that mangroves buffer only 0.42% of the global fossil fuel emissions (as of 2014) due primarily to their limited spatial extent in the coastal zone.

Climate change mitigation is, however, likely to be more significant and effective at the national scale especially in countries losing mangroves rapidly, such as in Indonesia and Myanmar (Taillardat et al. 2018). An estimate of national mangrove sequestration potential showed that they can contribute significantly to mitigation of CO_2 emissions if deforestation rates remain low (Taillardat et al. 2018). For example, mangroves in countries such as Nigeria, Colombia, Bangladesh, Ecuador, and Cuba accounted for $>1\%$ of national CO_2 emissions. In countries with high deforestation rates such as Malaysia and Myanmar, the carbon storage potential of remaining mangroves was less than the carbon emissions generated by deforestation. In some countries, mangrove mitigation potential is a significant percentage of national losses, such as Papua New Guinea (34.9%), Gabon (11.3%), Panama (8.3%), Mozambique (8.3%), and Cameroon (8.4%), underscoring the importance of mangrove mitigation at the national and regional scale.

National-scale mitigation raises the issue of the viability of mangrove blue carbon financing (Alongi 2018; Zeng et al. 2021) as the protection or restoration of blue carbon is steadily gaining credence as a key natural climate solution with a recent spike in public and private sector interests and investments for nature-based carbon financing mechanisms. The success or failure of a blue carbon project depends on multiple factors, including increased involvement from key stakeholders and constraints by knowledge gaps in both management, science, and carbon markets. An extensive analysis of the potential and limits of mangrove projects for climate change mitigation (Zeng et al. 2021) modelled the magnitude of certifiable carbon from mangrove blue carbon projects and its mitigation potential as well as the relative profitability of these projects to produce a global map of mangrove blue carbon return on investment. The analyses indicated a limited global potential with only ~20% of the world's mangrove forests qualifying for blue carbon funding and only ~10% financially sustainable for over 30 years. However, this small percentage would contribute up to 29.8 $MtCO_{2eq}$ a^{-1} and yield a return on investment of ~US

\$3.7 billion a^{-1}. These results point to a disproportionately large potential of blue carbon finance that can be leveraged to meet national climate mitigation goals, especially coupled to other conservation goals to protection mangrove carbon stocks and biodiversity (Zeng et al. 2021).

8.4.2 Future CO_2 Emissions

A predictive model of mangrove carbon emissions (Adame et al. 2021) has recently projected emissions and soil carbon sequestration potential under 'business as usual' rates of mangrove loss. Emissions could reach up to 2391 Tg CO_{2eq} by 2100 and would increase up to 3392 Tg CO_{2eq} if soil carbon sequestration is included. About 90% of these emissions are predicted to come from Southeast and South Asia (west Coral Triangle, Sunda Shelf, and Bay of Bengal), followed by the Caribbean (tropical Northwest Atlantic) and Andaman coast (west Myanmar) and north Brazil shelf (Fig. 8.4).

The west Coral Triangle, the Sunda Shelf, and the Bay of Bengal had the highest predicted emissions (712 Tg CO_{2eq}, 452 Tg CO_{2eq}, and 369 Tg CO_{2eq}, respectively) due to losses to agriculture/aquaculture at 985 Tg CO_{2eq}, contributing to 73% of emissions (Fig. 8.4). Erosion was an important driver of loss in these provinces,

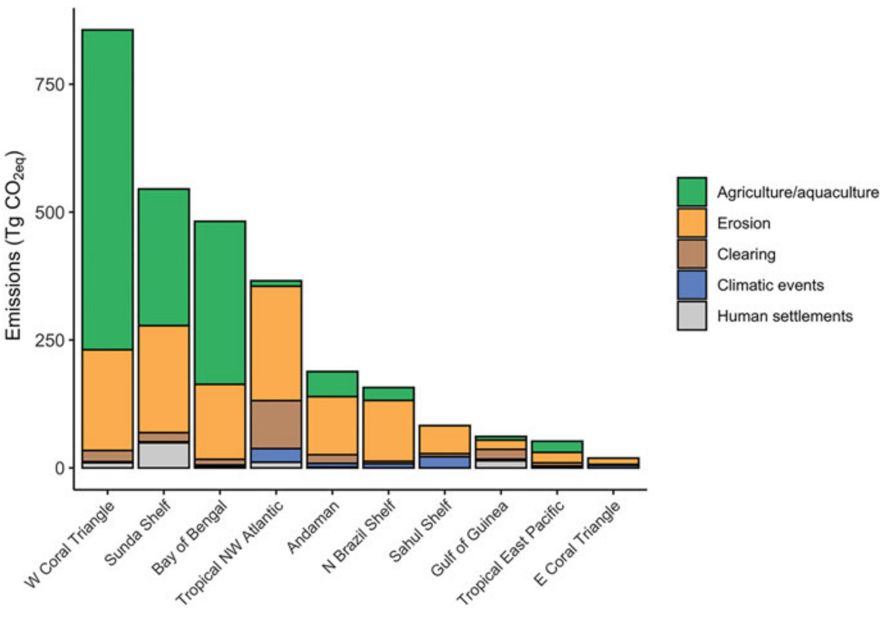

Fig. 8.4 Cumulative CO_{2eq} emissions (Tg) over the 2010–2100 period attributed to the proximate drivers of mangrove loss for the marine provinces ranked in the top ten for future CO_2 emissions (reproduced from Adame et al. 2021. Licensed under CC BY 4.0)

accounting for 23%, 38%, and 30% of their emissions, respectively. Erosion was similarly a large driver of mangrove loss in the Andaman (west Myanmar, Bangladesh, and east India) province, accounting for 98 Tg CO_{2eq} or 60% of its total emissions. Another hotspot for mangrove carbon emissions was predicted for the tropical northwest Atlantic which had large emissions due to erosion (191 Tg CO_{2eq}), clearing (80 Tg CO_{2eq}), and extreme climate events (23 Tg CO_{2eq}) with total emissions projected to reach 312 Tg CO_{2eq} by 2100 (Fig. 8.4). Lower CO_2 emission hotspots were predicted to occur on the north Brazil shelf, the Sahul shelf, Gulf of Guinea, tropical east Pacific, and east Coral Triangle (Fig. 8.4). Thus, most mangrove carbon losses by the end of the century will be the result of natural and anthropogenic factors, especially cultivation, erosion, and clearing, rather than as a direct result of climate change. This may provide humanity with a window of opportunity to address the forces currently resulting in mangrove decline.

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Chapter 9
Rehabilitation and Restoration of Mangroves

Sudhir Chandra Das

Abstract Successful mangrove rehabilitation or restoration is the accurate attention to local hydrology and basic biology of mangrove trees and their associated fauna. Long-term success of mangroves depends on far more axes, each with their own challenges. In the context of a rapidly changing climate, mangrove restoration projects must be able to adopt and evolve both geo-morphologically and socio-economically important aspects of the ecosystem over decades-to-centuries. Restored and rehabilitated mangrove ecosystems have important ecological, economical and social values for coastal communities. They provide livelihoods and can be deliberately designed and engineered to facilitate and provide valuable ecosystem services such as coastal protection. In spite of their importance, mangrove ecosystems are under extreme biotic pressure from human activities. Mangrove trees are being felled and removed for firewood, agriculture, coastal development and to make way for shrimp farming. They are falling victim to pollution from inland sources such as discarded plastics, untreated sewage and nutrients from agriculture. Immediate attention is required for proper planning to restore mangroves. Current pressures mean mangroves need immediate attention for proper planning to rehabilitate and restore mangroves. Both the successes and failures of restored mangrove ecosystems can help to develop platforms for educating non-specialists about the importance of mangrove restoration and rehabilitation. Immediate attention is required for proper planning to restore mangroves.

Keywords Mangrove · Restoration · Ecosystem · Climate Change · Coastal Community

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9.1 Introduction

Mangroves are found in tropical areas with high solar radiation and precipitation (Numbere and Camilo 2016). Mangroves are taxonomically a diverse group of ±70 tree, shrub and fern species (in approximately 25 genera and 19 families) that grow in anoxic and saline peaty soils on sheltered, tropical coasts (Tomlinson 2016). Mangroves inhabit the interface between the land and the sea. This habitat specialist plant group grows along coastal regions in swampy soil that is continuously wet from year to year because of the action of tides and heavy rainfall. Mangroves can be found throughout the tropics, with representatives of the major mangrove genera *Rhizophora* and *Avicennia* present in both the Indo-West Pacific (IWP) and the Atlantic, Caribbean and Eastern Pacific (ACEP) realms (Ellison et al. 1999; Tomlinson 2016). Mangrove species diversity is much lower in the ACEP, where it reaches a maximum of 8–9 species at any given site, than in the IWP, where 30 or more species from the regional pool of at least 46 can co-occur (Ellison et al. 1999). At least 16% of mangrove species worldwide are currently considered to be of conservation concern (Polidoro et al. 2010).

Mangrove restoration is the regeneration of mangrove forests either naturally or artificially in areas where they have existed previously. The practice of mangrove restoration is included in the discipline of restoration ecology, which aims at assisting the recovery of resilience and adaptive capacity of ecosystems that have been degraded, damaged or destroyed due to biotic pressure. Since environmental impacts are an ongoing threat to restore successfully an ecosystem, implies not merely to recreate its former condition but to strengthen its capacity to adapt to change over time.

We are living in the era of ecosystem rehabilitation and restoration (Wilson 1992). Restoration ecology has progressed rapidly from its initial unrealistic 'eco-centric' goal of eliminating or compensating human influences on ecosystems (Jordan and Lubick 2011) to its current 'meliorative' framework of creating and maintaining sustainable socio-ecological systems (Kibler et al. 2018; Krievins et al. 2018). Methods and approaches for rehabilitating and restoring coastal and marine ecosystems have progressed rapidly. It is now realistic to envision that many coastal and marine ecosystems could be substantially to completely rebuilt by the middle of this century with concerted effort and careful attention to climatic change (Duarte et al. 2020).

Mangrove forests are highly productive ecosystems with rates of primary production equal to those of tropical humid evergreen forests (Alongi 2014). They accumulate carbon in tree biomass, and most of this carbon is lost by decomposition and export to adjacent ecosystems (Alongi 2012). Mangroves play also a key role in human sustainability and livelihoods, being heavily used for food, timber, fuel and medicine (Alongi 2002). They offer protection from catastrophic events, such as tsunami, tropical cyclones and tidal bores and can dampen shoreline erosion (Alongi 2014). However, the importance of mangroves is a relatively new notion. 'Mangroves prior to 1970 were generally considered to be mosquito-infested swamps that nobody needed really to worry about and if you wanted to destroy them, that were okay', says Robin Lewis (2005), an ichthyologist-turned-wetland scientist who now restores mangroves around the world.

Unfortunately, a better understanding of mangroves' importance has not stopped their destruction. Nearly 36,000 square kilometres of mangrove forests were destroyed between 1980 and 2005, according to the United Nations and the losses continue today (less than 155,000 square kilometres remained in 2005). Mangroves are disappearing at a global loss rate of 1–2% per year (Spalding et al. 2010), and the loss rate reached 35% during the last 20 years (FAO 2007). Climate changes (sea level rise and altered rainfalls) and human activities (urban development, aquaculture, mining and overexploitation of timber, fish, crustaceans and shellfish) represent major threats for mangrove habitats (Ellison and Zouh, 2012). Habitat loss is typically associated with a loss in terms of biodiversity.

To make up this loss, people attempt to restore mangroves all around the world. In most cases, they approach mangrove restoration as if they were planting a forest on land. They grow mangrove seedlings in nurseries/green houses and then transplant them into mudflats along the ocean's edge. The problem is that this approach does not work very well. In the Philippines, for instance, the World Bank spent $35 million to plant nearly 3 million mangrove seedlings in the Central Visayas between 1984 and 1992. But by 1996, less than 20% of those mangroves had survived (Walters 1997). Establishment of mangroves hardly reaches 30% due to tidal effects, which is why attention should be paid to mangrove restoration.

9.2 Why We Need Mangrove Restoration?

Mangroves are critical coastal ecosystems that impact the lives of the people residing in and around the coastal areas providing food, medicine, fuel and building materials for local communities. Mangroves nourish biodiversity as they are nursery and breeding grounds for many coastal and marine species and this in turns supports commercial fisheries. The roots of the mangrove physically buffer shorelines from the erosive impacts of ocean waves and storms. Additionally, they protect riparian zones by absorbing floodwaters and slowing down the flow of sediment-loaded river water. This allows sediments to drop to the bottom where they are held in place, thus containing potentially toxic waste products and improving the quality of water and sanitation in coastal communities.

Mangroves buffer coastal communities against extreme weather events such as hurricanes, tsunamis, stabilise coastlines, bind silt/soil particles and reduce soil erosion. On a global scale, they have been shown to sequester carbon in quantities comparable to higher-canopy terrestrial rainforests, which means that they may play a role in climate change mitigation (Spalding et al. 2010) in addition to physically protecting coastlines from the projected sea-level rise associated with climate change. However, there are limits to the capacity of mangroves to adapt to climate change. It is projected that a 1-meter rise in sea level could inundate and destroy mangrove forests in many regions around the globe (IPCC 2001), which would leave coastal communities vulnerable to the risks of flooding, shoreline erosion, saline intrusion and increased storm activity (Field 1995).

Mangroves have high economic value, especially to coastal people. Mangroves alone contribute ≈ US $174–249 million each year to the country's economy (Cooper et al. 2009). Despite this benefit, half of the world's mangroves (about 3.2 million hectares) have already been cleared or destroyed—and those that remain are under threat. Once it is gone, it may be gone forever, as regeneration and establishment of mangrove are difficult tasks because of their slow growth and regular tidal inundation. So, it should be restored with utmost care. IUCN and The Nature Conservancy are producing a global map with cutting edge analysis on the potential for, and challenges to, mangrove restoration. The map aims to stimulate commitment among decision-makers and investors for mangrove ecosystem restoration on a landscape scale.

9.3 Mangrove Ecology

Before discussing mangrove restoration, the ecology of mangroves should be understood. Mangroves are unique ecosystems having diverse and distinct structural and functional attributes exclusive to them. Mangrove forests grow generally on the creek sides in the intertidal coastal areas where rivers meet the seas. These mangrove soils are frequently inundated with sea water during high tides which contains highly soluble salts and are physiologically dry. The soluble salts are deposited in the soil phase which leaches out during rain. However, further salt deposition may occur due to frequent tidal flooding. The sub-soil salt also comes up to the surface by capillary action of the soil water during the dry summer months. The salty surface soil does not allow plant species to grow except a few herbaceous salt-tolerant halophytic floras, e.g. *Heliotropium curassavicum, Sesuvium portulacastrum, Alternanthera paronichioides* and a few grasses and sedges. Within a period of 13–15 years, an area can be completely changed from the initiation of its depositional phase to a destructive phase. For example, in India (South Asia), the most important mangrove tree species *Heritiera fomes* cannot anchor satisfactorily in these ever-changing ecological conditions.

The total mangrove flora can be grouped into two distinct habitats. One group prefers to grow and survive under direct sunlight while the other group prefers to grow and survive under slightly shady condition. The former group includes *Acanthus ilicifolius, Avicennia marina*, *A. alba*, *Sonneratia apetala* and *S. griffithii*. The latter group includes *Aegiceras corniculatum*, *Bruguiera gymnorhiza*, *Ceriops decandra*, *Rhizophora apiculata*, *R. mucronata* and *Lumnitzera racemosa*. The viviparous, crypto-viviparous and other interesting type of germinated seedlings can be distributed naturally within the high-tide level and the intertidal zone (see Chap. 2).

Reinder Gouwentak (Reinders-Gouwentak 1953) reported the relationship between the structure of the mangrove and their physiology while Uphof (1941) reported the xeromorphic nature of the mangroves. Schimper (1891) also classified these mangrove species among the xerophytes, as these plants grow in highly saline soil, i.e. physiologically dry soil. MacNae (1968) compared the transpiration rate among the *Avicennia marina, Rhizophora mucronata* with that of the *Mangifera indica* (a mesophytic plant) under similar temperature and humid conditions, where transpiration rate of the mangroves was noted more than the mesophytic plant species. Understanding different species ecology helps with restoration of the mangrove ecosystem.

9.4 Mangrove Restoration

A positive feature for mangrove ecosystem management is that mangrove forests are relatively easy to restore through natural regeneration, or via artificial restoration using planted seedlings. Natural re-colonisation is always preferable to planting mangroves because it means that the most appropriate species occupy the shoreline and natural succession can take place. However, many of the functions and attributes of mangroves, including their productivity and biodiversity support can be regained through artificial restoration. The planting of mangroves is simple, but to be effective mangrove restoration must be undertaken carefully, with the following activities planned and budgeted for:

1. Site selection including detailed assessment of the hydrological conditions.
2. Species selection; tree spacing, thinning and maintenance criteria established.
3. A forest protection and monitoring system introduced.
4. A public information and awareness-building programme incorporated in support of the restoration effort.

As much as possible, mangrove restoration should involve mixed species planting, or at least species other than the *Rhizophora* spp. should be included.

Mangroves are sensitive ecosystems, changing dynamically in response to storms, sediment blockage and fluctuations in sea level (Field 1998) and present a ‘moving target’ for restoration efforts. Different restoration approaches face this challenge in different ways. The most common method simply consists in planting single-species stands of mangroves in areas thought to be suitable, without consideration of whether or not they supported mangroves in the past. This approach usually fails over the long term because the underlying soil and hydrological requirements of the mangroves are not being met. More informed methods aim to bring a damaged mangrove area back into its pre-existing condition, taking into account not only ecosystem factors but also social, cultural and political perspectives (Field 1998). These approaches begin with the understanding that a damaged mangrove area may be able to repair itself through the natural processes of secondary succession, without being physically planted, provided that its tidal and freshwater hydrology is functioning normally and there is an adequate supply of seedlings (Lewis 2005). Taking this into account, it becomes crucial to the success of a restoration project to evaluate what the hydrology of a disturbed mangrove site should look like under normal conditions, and the ways in which it has been modified. One example of this approach is the Ecological Mangrove Restoration method (Lewis 2005) which recommends the following steps, to be undertaken using healthy mangroves of the surrounding area as a reference:

1. Assess the ecology, especially reproduction and distribution patterns, of the mangrove species at the disturbed site.
2. Map the topographical elevations and hydrological patterns that determine how seedlings should establish themselves at the site.
3. Assess the changes made to the site that currently prevent the site from recovering by itself.
4. Design a restoration plan that begins by restoring the normal range of elevations and tidal hydrology at the site.
5. Monitor the site to determine if the restoration has been successful in light of the original objectives.

The actual planting of seedlings is a last resort, since it fails in many cases, it should be considered only if natural recruitment of seedlings fails to reach the restoration objective. Mangrove restoration can be done either by natural regeneration or by artificial regeneration.

9.4.1 Natural Regeneration

Under favourable conditions, mangrove trees regenerate freely from seed and natural seedling regeneration is almost satisfactory (Fig. 9.1). The necessary condition appears to be frequent flooding and absence of dense low cover which the seedlings do not tolerate. The lowering of water level results in cessation of reproduction. The places beyond the reach of high inundations are adverse to the growth and eventually it dies off. A dense growth of *Acanthus ilicifolius* prevalent in some localities also tends to kill mangrove seedlings but, in some areas, it has been found that *Acanthus* helps regeneration when not too dense by keeping out other arborescent species and giving protection to escape from browsing by cattle.

Regeneration of mangrove species is obtained partly by seeds falling in the water which drift into the felled areas during tidal inundation and partly by retaining the advance growth which comes up under the cover of the older trees and amongst the thickets of *Acanthus ilicifolius*. The species being a light demander respond rapidly to full overhead light and form the chief source of regeneration in the felled areas. However, for satisfactory natural regeneration, several favourable circumstances are considered necessary such as:

Fig. 9.1 Natural regeneration of mangroves in tidal areas (**a**) *Aegialitis rotundifolia* (above) and (**b**) *Ceriops decandra* (below) in Sundarbans

1. Proper tidal conditions during the short period in which the viviparous seeds are on the parent trees.
2. A reduction in the salinity of water so as to stimulate the growth as soon as the roots strike the ground.
3. Freedom from prolonged re-flooding until the seedlings emerge from the soil and get their head above flood level.

Difficulties regarding natural regeneration are met when the land is beyond the reach of tidal inundation and becomes unfit for tidal species. Then the land turns gradually into blanks or is occupied by grasses or bushes like *Suaeda*. On sites still suitable for growth of tidal species, biotic factors such as heavy grazing by wild animals or domestic cattle or excessive felling often impede natural regeneration. However, once these impediments are removed, natural regeneration readily returns. The retention of trees along banks of water channels combined with a thick mass of undergrowth of species like *Acanthus* helps in natural regeneration and affords protection to the seedlings against browsing.

The main mangrove tree species in the Sundarbans is *Heritiera* and can regenerate in both salt water and fresh water prolifically and develop satisfactorily under shade of the existing crop on suitable sites. Similar is the case with associate species like *Excoecaria agallocha*. Excessive browsing by deer or cattle in some localities is responsible for failure of natural regeneration. If fencing is provided, natural regeneration of the desired species will come up and lead to the establishment of natural regeneration. *Ceriops decandra* often forms a thick understory in the mangrove tree forest and is one of the main constituents in the upper canopy in the mangrove scrub and primarily regenerates through existing root suckers which are normally plentiful.

9.4.2 Artificial Regeneration

The necessity for artificially regenerating areas is sometimes undertaken to supplement the natural regeneration by collecting the embryos off the ground after they fall and sticking them vertically in the mud. Mangrove afforestation techniques are based on available information in records, traditional practices and conventions which may differ from site to site even within a particular region. Exact practices for afforestation should be site-specific. Establishing a mangrove nursery ensures ready supply of seedlings of different species of mangroves for raising mangrove plantations (Fig. 9.2).

Fig. 9.2 Propagules of *Avicennia officinalis* (left) collected for planting and nursery raised seedlings of *Bruguiera gymnorhiza* (right) in Sundarbans

9.4.2.1 Selection of Site for Mangrove Restoration

The following factors should be kept in mind for selection of a suitable site for restoration of mangroves.

- Soil and water salinity.
- Ground Level/ground elevation.
- Frequency and height of tidal inundation.
- Mangrove species and vegetation present are the indicators of species suitability.
- Extent of wave action.
- Presence or absence of pests.
- Selected sites should be adjacent to existing patches of natural mangroves.
- Selected sites preferably are closer to low-tide mark where tidal inundation is assured.

9.4.2.2 Choice of Species on the Basis of Salinity

On the basis of mangrove preference vis-à-vis water salinity, mangrove species should be selected. Success of artificial regeneration largely depends on the choice of species.

- **Mangrove Species Suitable for High Salinity:** *Ceriops decandra, Bruguiera gymnorhiza, Xylocarpus mekongensis, Avicennia* spp., *Excoecaria agallocha, Xylocarpus granatum, Aegialitis rotundifolia.*
- **Mangroves Species Suitable for Low Salinity:** *Sonneratia caseolaris, Sonneratia apetala, Bruguiera gymnorhiza, Nypa fruticans, Heritiera fomes, Phoenix* spp.

9.4.2.3 Choice of Species on the Basis of Ground Elevation

Low ground	Medium ground	High ground
Rhizophora apiculata	*Avicennia marina*	*Excoecaria agallocha*
Sonneratia caseolaris	*Bruguiera cylindrica*	*Ceriops decandra*
Avicennia alba	*Ceriops tagal*	*Bruguiera gymnorrhiza*
Kandelia candel	*Avicennia officinalis*	*Heritiera fomes*
Sonneratia apetala	*Aegialitis rotundifolia*	*Xylocarpus granatum*

9.4.2.4 Flowering, Fruiting and Fruit/Seed Collection Time of some Mangroves

The flowering, fruiting and seed collection time of mangroves may vary country to country. The flowering and fruiting time of mangroves of the Sundarbans are given in the following table as an example (Table 9.1).

9.4.2.5 Collection of Seeds/Propagules

Mangrove seeds are buoyant and are thus able to disperse through water. The tidal creeks are often full with the large seeds floating on the surface of the water about August-September in the Sundarbans and most of the seeds have been found to be germinated. Mature fruits or propagules usually washed away from the high-tide zones near identified trees should be collected during low tide or by hand net from creeks and graded for healthy ones which are free from disease or insect attack.

Table 9.1 Important mangrove species and flowering and fruiting times in the Sundarbans to plan for collection for restoration

Name of important mangrove	Flowering time	Fruit	Fruiting time
Avicennia alba	May–June	Greyish green capsule of 1″ length containing one seed	September–October
Avicennia marina	April–May	Greyish green capsule of 1″ length containing one seed	August–September
Ceriops decandra	April–May	Viviparous with thin, long hypocotyls	July–August
Ceriops tagal	April–May	Viviparous with thin, long hypocotyls	July–September
Sonneratia caseolaris	April–May	Spherical berry with numerous seeds	August–October
Nypa fruticans	May–September	Large fruiting head	March–April
Excoecaria agallocha	April–May	Small dark capsule	June–September
Aegiceras corniculatum	February–March	Curved, viviparous; Pericarp splits vertically	July–September
Heritiera fomes	March–April	Large, spherical, corky leathery; splits into 4 when dry	May–September
Xylocarpus mekongensis	February–September	Large, spherical, corky leathery; splits into 4 when dry	February–March
Xylocarpus granatum	February–October	Same as above	February–March
Sonneratia apetala	April–May	Spherical berry with numerous seeds	August–September
Rhizophora apiculata	March–April	Green or brown viviparous fruits, contain one seed	August–September

Mature seeds/propagules can also be collected from trees. Seeds should be kept in the shade in moist conditions prior to planting.

9.4.2.6 Nursery Techniques

Site selection is the first important step in establishment of a mangrove nursery. The major requirements for a mangrove nursery site are-

- Sheltered intertidal areas away from the direct flow of big rivers with periodic inundation (Fig. 9.3). The site should not be waterlogged for easy working.
- Access to good quality salt water and fresh water.
- Availability of water during the neap tides and summer (provision for tranches and fresh water).
- Easy transport and labour availability for carriage to planting site.

A nursery is required for plantation of *Bruguiera*, *Rhizophora*, *Ceriops*, *Aegialitis*, *Sonneratia*, *Xylocarpus*, *Phoenix* and *Nypa*. However, some of the above plants can be sown or planted directly in the field, e.g. *Avicennia*, *Bruguiera*, *Rhizophora* and *Ceriops*. The saplings of *Sonneratia* are planted directly in the plantation area after trimming the roots and stem. During low tide, its floated seeds

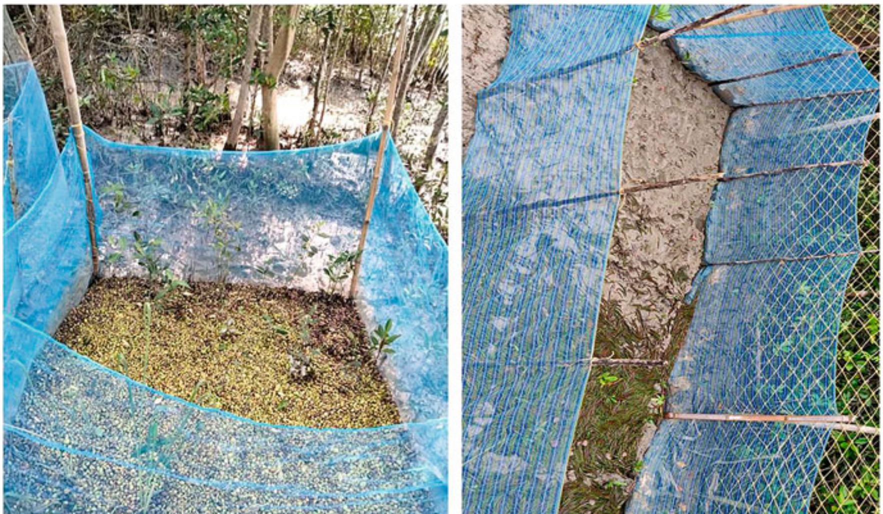

Fig. 9.3 Sheltered inter-tidal areas with periodic inundation for seed germination, *Avicennia* spp. (left) and *Ceriops* spp. (right)

are usually sown on the silt accumulated area near the embankments. When the sprouts are 5-cm long, they are planted at the plantation side during low tide. *Sonneratia* seeds can be sown on the mother bed like Eucalyptus seeds.

- In case of *Phoenix paludosa*, the seedlings are first prepared like the Date palm before being planted in the plantation area.
- In case of *Nypa fruticans*, the mature dark brown seeds are packed in a jute bag and are exposed to high- and low-tide for several days. The sprouted seeds are planted on the mother bed. When the saplings are 15 cm long, they are taken out from the mother bed for planting.

9.4.2.7 Artificial Regeneration Techniques

Mangrove plantation on the fore-shore mudflats of the river is done during low tides when the water recedes. *Exoecaria* sp. seedlings are generally planted at 2.5 m apart in the first line. In the next lines, seedlings of *Heritiera fomes*, *Sonneratia apetala*, *Xylocarpus granatun*, *X. mekongensis*, *Rhizophora mucronata*, *Avicennia* spp. are planted and/or propagules (pre-germinated seeds) are sown 1 m apart in 30 cm × 30 cm pre-silted trenches (Fig. 9.4). In the lower portion where Dhani grass (*Oryza coarctata*) is coming up, *Avicennia officinalis, A. alba, A. marina* are planted and above it, *Ceriops tagal*, *Sonneratia apetala*, *Xylocarpus granatum* and *X. mekongensis* are planted at 2.5 m × 2.5 m apart. At the sides of creeks, *Rhizophora mucronata* and *Bruguiera gymnorhiza* may be planted. The stock of *Nypa fruticans* is often augmented through sowing on chars (bank of creeks) or treeless blanks which are below the usual high-tide level. Pre-germinated seed is placed loose on the ground and tops of grass tufts surrounding it are tied, so that the seeds can move up and down freely with the tidal water and escape being buried in the silt. In the Cauvery delta, *Avicennia officinalis* regenerates itself very successfully. Small blanks which appear here and there are broadcasted with fresh seeds collected by dragging a net over the water in the creeks with good mother trees around. The seeds of *Nypa fruticans* are well pressed into the mud by feet after sowing. The best time for sowing is between the new moon and full moon.

Seeds which are regularly flooded have good germination and better growth (Madan 1930). Madan (1930) recommended cutting a number of small channels which would also facilitate transport of produce. In the past, attempts were made to raise mangroves artificially in blanks by direct sowing but these were discontinued after a few trials due to the uncertain results achieved. One of the reasons for failure of artificial regeneration of mangrove is accumulation of thick layer of sand and silt on the top of the mud (Qureshi 1957).

9.4.2.8 Hurdles in Mangrove Regeneration

There are many hurdles to successful mangrove regeneration.

Fig. 9.4 Artificial regeneration (planting) of *Avicennia* during low tide on the mudflats in the Sundarbans and in pre-silted trenches by local communities

- The major obstacle in the Sundarbans is the extensive catching of tiger prawns (*Penaeus monodon*) with mosquito nets by local people along the fore-shore areas causing damage to the young plantations in a massive way.
- Secondly is the unwillingness of certain local people against mangrove afforestation. These people are ignorant about the importance of this fragile coastal ecosystem and its degradation.
- Thirdly is natural calamity. Sometimes the height of water level crosses 3 m above M.S.L in plantation area during high tides and rate of siltation is so high that seedlings are submerged and succumb to death.

9.5 Mangrove Protection

When mangrove forests are cut, they release stored carbon into the environment. Blue carbon emissions have increased significantly as a result of mangrove deforestation. Mangrove losses for the period 1980–2005 are estimated to be more than three million hectares. It is crucial to restore and enrich them. To arrest the recent and rapid destruction of coastal mangrove ecosystems, to improve their management and to conserve biodiversity in these critical natural habitats, direct interventions are required to promote natural regeneration where mangrove ecosystems have the capacity for self-renewal, to rehabilitate degraded mangrove ecosystems, to protect and enforce mangrove buffer zones and to increase livelihood opportunities from government and non-government organisations. The Mangrove Restoration Action Group in the Commonwealth shares best practices and organises mutual co-operation in the conservation and sustainable utilisation of mangroves through:

- Developing a database on mangrove ecosystems in the Commonwealth.
- Sharing technical know-how on valuing the economic contribution of mangroves to coastal livelihoods through fishing and ecotourism.
- Creating strategies to strengthen legal frameworks for conservation of mangroves.
- Strengthening community partnerships for the management and resource ownership of mangrove ecosystems.
- Declaring protected mangrove areas to ensure legal protection.

Sri Lanka has stepped forward to be a Commonwealth Blue Charter Champion and lead an Action Group on Mangrove Restoration. The country is home to nearly 16,000 hectares of mangroves. It has taken a number of significant measures to conserve and manage mangroves in order to safeguard biodiversity and the contribution of mangroves to the ecosystem.

Mangroves are fragile ecosystem and difficult to regenerate. So, it can be protected by involving government agencies (GOs), non-government organisations (NGOs) and local communities. By protecting mangroves, crucial ecosystem services that mangroves provide, water filtration and treatment and coastal defence (Barbier et al. 2011; Horchard et al. 2019) can be ensured. Mangrove rehabilitation and restoration projects may also mitigate some effects of climatic change. Governments of every mangrove bearing country will try to protect this fragile ecosystem by involving local people through motivation and sharing usufructs among them. Most of the mangroves in India are protected by involving local communities through the formation of Joint Forest Management Committees (JFMCs). Here local communities are engaged in the protection and management of forests, in turn they are getting 40–50% share of net income derived from the forestry activities and ecotourism. The concept of participatory forest management can be adopted everywhere to protect and manage the mangroves.

9.5.1 Participatory Management

People's participation has now been recognised as essential for the success of forestry development. The concept of people's participation to many of us is still obscure. Does it mean merely to give employment opportunity to rural people or share of forest produces as benefit to the fringe populations residing in and around the forests? The intimate and intensive participation where local people act as equal partner with Forest Department has to be achieved through this approach. Developing a meaningful partnership with the community through the involvement of local people in decision making processes for management of the resources and conservation of the ecosystem is required. There is no denying the fact that the issues in management of natural resources are often highly location- specific and therefore, deserve careful scientific and technological inputs. But indigenous knowledge and grass-root level technology can be the beginning of a viable joint management practice. The key ingredients should be the involvement of decision makers and local people in the forest and wildlife protection, management, training and administration in the field and pulling the disciplines from the social, biological and physical sciences in addressing the complex environmental problems.

9.5.2 Eco-Development/JFM Support Activities

Management changes of mangrove forests from exploitation to protection systems have definitely led to hardship of forest user groups due to lost access and income from forests. Action plans must offer employment opportunities specifically for target groups, not only through silviculture-based forestry operation but also through support services which are ecologically compatible to meet the needs of the community. In response to pressures on protected areas, the Indian Government is now beginning to address the special issues regarding participatory management of protected areas through a strategy of eco-development. The strategy aims to conserve biodiversity by addressing both the impact of local people on protected areas and impact of protected areas on local people. Eco-development thus has two main thrusts: (i) improvement of forest/protected area management and (ii) involvement of local people. In doing so, it seeks to improve the capacity of forest/protected area management to conserve biodiversity effectively and to involve local people providing incentives for conservation and support sustainable alternatives to harmful use of resources (Guha Bakshi et al. 1999). A schematic diagram is given below highlighting management interventions towards Joint Forest Management (JFM) (Table 9.2).

Success of participatory management through eco-development depends on proper micro-planning which is a process of planning at the grass-root level involving the local people for optimum utilisation of the available resources according to the people's need. Such micro-plans are prepared by adopting a method of

Table 9.2 Management interventions towards Joint Forest Management of mangrove ecosystems in India

Management interventions towards joint forest management (JFM)	
Strategies	Actions
Trust building activities (entry point)	Rain water harvesting structures Sharing of tourism revenue Medical camps Veterinary camps Drinking water treatment plant
Agriculture related initiatives	Re-excavation of irrigation channels Providing agricultural inputs Supply of salt-resistant crop variety and high yielding variety seeds
Infrastructure development	Construction of school building Brick paved path Construction of jetties Installation solar lights Development of flood relief shelters
Alternate livelihood program (alp) & capacity building	Supply of Van rickshaw Piggery, Goatery, poultry Apiculture boxes, Pisciculture, House keeping training to local youths, handicrafts, vocational trainings
Institutionalisation	"Self help group (SHG)" formation
Awareness generation	Study tour of Villagers & School Children Ban-Mahotsav, wildlife week Global Tiger day Celebration Inter-JFMC football tournament
Sectoral integration	Involvement of all line departments, Panchayets, civil administration keeping Forest Department as nodal agency

Participatory Rural Appraisal (PRA). In the first stage of the process, the local need is assessed followed by resources identification. In the planning process, the budgetary allocations are matched according to the need assessment and resources available.

9.5.3 Awareness Campaign

Awareness generation among the people is one of the major tools for protection of mangroves. The importance of mangrove forests should be highlighted in text books and in the media to educate both students and lay people. Awareness campaigns should be initiated in schools and local market places to make people conscious about the benefits derived from the mangrove forests. Posters and hoardings can be put in important places for the awareness of the people. In the villages adjoining mangrove areas, video shows can be organised in the villages to educate and raise awareness of the local people. So many extension education programmes are available which can be adopted to protect the mangroves.

9.6 Conclusions

The issue of restoration is critical today since mangrove forests are being lost very quickly—at an even faster rate than tropical rainforests. Mangroves are sensitive ecosystems, changing dynamically in response to storms, sediment blockage and fluctuations in sea level and present a 'moving target' for restoration efforts. Habitat loss and conversion are two major threats that can lead to the extinction of mangrove forest if not checked. People's participation and integration of participatory adaptive management frameworks used throughout the world should be adopted. Long-term success of any rehabilitation or restoration project must bring together ecology, sociology, economics and governance through community involvement to define, measure, monitor and update project objectives and goals. Urgently, it is important to embark on deliberate protective measures, which can prevent the exploitation and plundering of the remaining mangroves resources in the world.

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Chapter 10
Threats to Mangroves and Conservation Strategies

Elizabeth C. Ashton

Abstract Mangroves are productive and biodiverse ecosystems found in the intertidal zones of the tropics and sub-tropics which provide multiple goods and ecosystem services for humanity that are of ecological, economical, social and cultural importance. However, mangrove ecosystems are vulnerable because of several threats. The threats vary globally, regionally and locally. Mangroves can be affected by several different threats simultaneously, or over time as land use patterns change. There are some natural threats such as shoreline erosion and typhoons but predominantly they are human induced such as overexploitation, conversion and encroachment of mangrove habitats for agricultural and settlement purposes, aquaculture, a decline in freshwater and silt deposition and heavy metal pollution. Together with predicted climate change including global warming, sea level rise and extreme weather events, there will be further threats to mangrove ecosystems in the future. Mangrove conservation, restoration and rehabilitation are now being addressed through international agreements, protected areas, integrated policies and planning, reformed government structures, capacity development and environmental education but mangrove biodiversity conservation policies cannot succeed unless there is also consideration given to livelihoods and local communities are involved in all aspects of mangrove planning and management to promote sustainable conservation of mangrove biodiversity for the future.

Keywords Impacts · Pressures · Management · Restoration · Protection · Policy

10.1 Introduction

Mangrove ecosystems are found on the coastlines and river deltas of the tropics and sub-tropics and currently face many threats. Some threats are natural such as shoreline erosion and typhoons but predominantly they are human induced

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Table 10.1 Range and scale of the threats to mangroves in three major regions of the world

Threat	South and Southeast Asia	Central and South America	Africa
Natural disasters	Low-high *Increasing*	High *Increasing*	Medium *Increasing*
Climate change	Medium-high *Increasing*	Medium-high *Increasing*	Medium-high *Increasing*
Population pressure	High *Increasing*	Low-medium *Increasing*	High *Increasing*
Over-exploitation by traditional users	High *Increasing*	Low *Stable-decreasing*	Medium *Increasing*
Urban and industrial development	High *Increasing*	Medium-high *Increasing*	Low *Increasing*
Coastal pollution	Medium-high *Increasing*	Medium-high *Increasing*	Low *Increasing*
Hydrological diversions, e.g. dams	Medium-high *Increasing*	Low-high *Increasing*	Localised medium-high *Increasing*
Forestry	High *Stable*	Low *Stable*	Medium *Increasing*
Aquaculture	High *Increasing*	High *Increasing*	Low *Increasing*
Agriculture	High *Decreasing*	Low *Stable-decreasing*	High *Increasing*
Mining	Low-medium *Decreasing*	Low *Decreasing*	Medium *Increasing*
Tourism	Low-medium *Increasing*	Low-medium *Increasing*	Low *Increasing*
Management shortcomings	Medium-high *Decreasing*	Low-high *Stable*	High *Stable*

Adapted from Macintosh and Ashton 2005

(Goldberg et al. 2020; Thomas et al. 2017). Humans can exploit mangroves in many ways and have many impacts upon them. The threats to mangroves vary globally, regionally and locally (Macintosh and Ashton 2005). Mangroves can be affected by several different threats simultaneously, or over time as land use patterns change (Table 10.1). Together with predicted human-induced climate changes, global warming and rises in sea level, there are going to be further extreme weather events and shoreline erosion (Field et al. 2014; Maina et al. 2021) with further long-term implications for mangrove ecosystems (Feller et al. 2017).

Mangrove ecosystems were described by early explorers as smelly and hostile environments (Mastaller 1997), which lead them to being undervalued and converted to alternative uses by European colonisers such as the mangrove bark used for the production of tannins and manufacture of leather (López-Angarita et al. 2016). Traditionally, local communities exploit mangroves for timber, thatch and fuelwood. Extraction of certain sizes and species and physical disturbance of the habitat mean that most mangroves have been affected to some degree and few are now pristine (Hogarth 1999). Local subsistence use of mangroves for fishing, food and medicines is undervalued but can be substantial and important (Bandaranyke 1998). Over-exploitation occurs when population pressure increases and there are other threats to livelihoods from outside influences.

Increasing populations and intense urbanisation have made many mangrove deltas into large cities, for example in Asia: Mumbai and Kolkata in India; Bangkok, Thailand; Manila, The Philippines and Jakarta, Indonesia. As well as urban and industrial development mangroves have been converted to agriculture such as oil palm plantation, aquaculture including intensive shrimp farming, salt ponds, forestry and mining (Ashton 2008; Richards and Friess 2016). Sometimes mangroves have faced indirect and accidental threats such as coastal pollution by oil (Amarachi and Kabari 2020; Duke et al. 1997) or alteration of hydrological regimes further upstream. Other off-site activities can lead to mangrove degradation through siltation and changes in water flow and water quality, especially salinity change and changes due to water pollution (Pons and Fiselier 1991). Contaminants may be directly toxic to some marine organisms and their effects may be instantaneous or cumulative. Introduction of exotic species can also cause loss of biodiversity and habitat through competition with native species.

Threats to mangroves predominantly cause a loss of mangrove area. Baseline data for original mangrove extent are unclear from scant historical mentions and marine charts and may never be realised (Alongi 2002) but since satellite remote sensing in the 1970s, global estimates have been estimated and changes monitored (Bunting et al. 2018; Giri et al. 2011; Spalding et al. 1997, 2010; Thomas et al. 2017; Valiela et al. 2001; Worthington et al. 2020). There has been substantial loss in mangrove area with loss in some regions of 50% to 80% (Wolanski et al. 2000) and also declines in terms of biological diversity and forest structure (Bryan-Brown et al. 2020).

An increasing understanding of the importance and value of mangrove ecosystems for provisioning ecosystem services, such as timber and fuelwood and fisheries, supporting and regulatory services such as nutrient recycling, habitat provision, shoreline protection and carbon storage (Lee et al. 2014; Donato et al. 2011) and cultural services (Liquete et al. 2013) has led to recognition of the environmental, social and economic impacts associated with the decline and degradation of mangroves. This is now being addressed through legislative, management, conservation and rehabilitation efforts across mangrove regions (Macintosh and Ashton 2005).

10.2 Natural Threats to Mangroves and Climate Change

Natural causes were attributed to 38% of total mangrove loss from 2000 to 2016, with shoreline erosion (SE) and extreme weather events (EWE) attributed to 27% and 11%, respectively (Goldberg et al. 2020). All mangrove regions are affected by SE and EWE such as cyclones, droughts, heatwaves or extreme floods. However, the Sundarbans seaward edge in Bangladesh had the highest loss with SE contributing to nearly 80% national losses and Oceania lost almost 50% mangrove due to EWE (Goldberg et al. 2020).

Shoreline erosion occurs as a result of sea level rise, rainfall, temperature and wave activity and with predicted climate change scenarios this will increase (Gilman et al. 2007, 2008; Chap. 8). In future, the threats will increase from more severe and intense extreme weather and shoreline erosion and this should be taken into consideration in government policy. Mangroves helped mitigate the deleterious impact of the 2004 tsunami waves (Kathiresan and Rajendran 2005) and provided protection against May 2008 cyclone in Myanmar (UNEP Report 2009). There is mounting evidence to prove that dense mangrove forests are natural shields against cyclones, storm surges and tsunamis (Sandilyan and Kathiresan 2015). Greenbelts and buffer zones where natural phenomena such as typhoons, tidal surges and cylones and natural geomorphic erosion processes have a significant adverse effect on the coastline should be adopted and given strict protection. For example in the Mekong Delta in Vietnam, a 500 m to 1 km wide green belt (Full Protection Zone) was enacted to protect the coastline from storm and flood protection (Macintosh and Ashton 2005).

10.3 Population Pressure

The primary agent of mangrove loss from 2000 to 2016 was human activity 62%, although only 3% was due to conversion of mangrove forests to human settlements and the loss and threat are declining (Goldberg et al. 2020). Rapid urban expansion was still seen into adjacent mangrove forests in Ho Chi Minh City, Vietnam and Bangkok, Thailand, Lagos, Nigeria and Conakry, Guinea but it declined from 2000 to 2016 by 65% (Goldberg et al. 2020).

However, pollution from human activities and settlements, including garbage, plastic, sewage, oil and industrial effluents, solid and toxic wastes are major threats to mangrove ecosystems. Harris et al. (2021) identified 54% of mangroves are within 20 km of >1 ton/year plastic pollution source. Waste disposal from urban, industrial, agriculture or aquaculture sources should be carefully regulated. The inputs of organic matter, nitrogen and phosphorus compounds into estuaries' coastal waters should be kept to an absolute minimum through the use of adequate treatment before discharge. This is particularly true in the more stagnant mangrove channels where eutrophication can lead to anoxic (oxygen depleted) conditions, and severe degradation of the aquatic system. This requires that appropriate practices to eliminate, minimise or mitigate the impacts of pollution should be enforced (Macintosh and Ashton 2005).

The legal framework should also provide mechanisms to ensure that full and independent Environment Impact Assessments (EIAs) are conducted for development activities that could impact on mangroves. Physical infrastructures such as embankments, roads, dikes, ponds and canals may affect the normal tidal flow, surface run-off and sediment deposition dynamics along mangrove coastlines, even if they are not physically located within mangrove areas. Thus, EIAs should include assessment of the impact of infrastructure development projects on the hydrological regime both upstream and downstream of the proposed development site (Macintosh and Ashton 2005).

Local communities and traditional indigenous peoples who are highly dependent on mangrove resources for their livelihoods should be involved in their conservation and management. Education and involvement in enforcement of sustainable levels of extraction can lead to positive protection of mangroves. For example, the fishermen associations Agreements of Sustainable Use and Mangroves (AUSCEMs) in Ecuador (Chap. 19) and Joint Forest Management Committees in India (Chap. 11). Sustainable livelihood options should be identified and encouraged within prescribed limits (e.g. catch size, licenses, harvest quota, zoning) such as small-scale artisanal fishing, crab catching, shellfish harvesting eco-tourism and apiculture. Where existing activities result in unsustainable utilisation of mangrove resources, alternative livelihoods and income- generating activities should be suggested with basic training and support given.

The cultural, historical and other traditional associations with mangroves should be protected and integrated into mangrove conservation and management plans. The values and potential applications of traditional knowledge related to mangroves such as the use of traditional medicinal plants should be documented (Chap. 5).

10.4 Forestry and Silviculture

Logging was the second most prominent anthropogenic activity to cause 8.3% global mangrove loss from 1996 to 2010 and was almost exclusively in Southeast Asia (Thomas et al. 2017). Mangrove forestry for example for wood chip was very unsustainable in Malaysia in the 1970s (Ong 1995). Woodchips and pulp for the paper industry from mangroves are still a threat in Indonesia. Fuelwood collected by local communities and the use of mangroves for grazing by cattle can cause significant local threats in Africa and Asia. Energy plantations of mangrove or another fast-growing timber tree such as Acacia for fuelwood in adjoining areas to protected mangrove areas could be managed so as to discourage conservation areas being cut for fuel wood consumption. Also the use of fodder depots can help reduce pressure of livestock grazing in mangrove areas.

The cutting of mangroves for fuelwood consumption and the making of charcoal can be managed sustainably. For example, the Matang Mangrove Forest Reserve in Perak, Peninsular Malaysia has been under sustainable management by the State Forest Department since 1902 under a 30-year rotation for charcoal production with thinnings at 15 and 20 years for poles, although predominantly mono-specific *Rhizophora apiculata,* it does have some protected virgin forest areas within its 40,000 ha (Goessens et al. 2014; Ashton 1999).

The management of mangrove forests should have clear objectives. If the area is pristine virgin mangrove forest or near pristine, it should be immediately protected and conserved for biodiversity. Areas should also be protected for biodiversity conservation to maintain all endemic and rare species such as the Tiger Reserve in Sundarbans. Priority should also be given to protecting mature stands that are reproductively viable, even in disturbed areas reproductively active trees and shrubs are valuable as seed stands that are important in sustainable forest management and restoration and rehabilitation of mangrove forests.

Assessment of mangrove forest via aerial photographs, satellite mapping (Bunting et al. 2018; Giri et al. 2011; Spalding et al. 1997, 2010, Thomas et al. 2017; Chap. 4), ground truthing and an in depth understanding of species composition, structure, biology and ecology (Chaps. 2 and 3) should be used to assess the area for mangrove forest management, silvicultural utilisation, restoration and rehabilitation. Natural regeneration should be allowed wherever possible. If natural recovery and regeneration does not occur, active interventions such as restoring the natural hydrology and mangrove planting will be required. Use local mangrove species for rehabilitation and if large areas are required to be planted, the establishment of mangrove nurseries may be necessary. Involvement of the local people at all stages from planning, to site selection and design, seed and propagule collection, nursery management, planting and maintenance and protection of mangroves is important.

There are many successes and failures of mangrove forest restoration, although not all are documented, or are difficult to obtain in non-peer reviewed literature and project reports, but some examples are given in the Country case studies in this book and in several other papers (Ellison et al. 2020; Field 1998; Lee et al. 2019; Lewis et al. 2019; Worthington and Spalding 2018). Survival of mangroves is 60–90% over 10 years and reasons for failures are typically where there is poor planning, a desire for a rapid fix, or a lack of ecological understanding leading to restoration of the wrong locations, or planting with the wrong species (Worthington and Spalding 2018). Mangroves are mostly restored with one species (175 cases) typically *Rhizophora apiculata, R. mucronata or Avicennia marina* but mixed species had better restoration outcomes and biomass production (Su et al. 2021). Habitat complexity and diversity are important to maintain for ecological function, biodiversity and abundance of associated mangrove fauna (Ashton et al. 2003a, 2003b), although the actual extent of biodiversity-function relationship is not known and further research required (Lee et al. 2014). The precautionary approach for multi-species restoration is advocated where possible.

Mangrove restoration has substantial potential to contribute to multiple policy objectives related to biodiversity conservation, climate change mitigation and sustainable development and offers positive benefit-cost ratios making it an effective form of ecosystem management (Su et al. 2021). Mangrove restoration opportunities exist in every region and a Mangrove Restoration Potential Map (maps.oceanwealth.org/mangrove-restoration/ (Worthington and Spalding 2018)) provides information globally, by region and country on total restorable area and values obtained for restored areas by ecosystem services of soil organic carbon, aboveground carbon, people protected, commercial fish catch and commercial invertebrate catch enhancement value.

10.5 Fisheries

Mangrove fisheries have worldwide importance in providing subsistence food and income for a wide range of stakeholders and millions of people. The fisheries production value of mangroves is USD 708–987 ha^{-1} $year^{-1}$ (Barbier et al. 2011). Mangrove species, density, habitat quality, area and primary productivity are important components in maintaining fisheries and providing suitable reproductive habitat and nursery grounds and sheltered living spaces. Loss of mangrove areas and degradation as well as overfishing has led to a loss in mangrove fisheries production and livelihoods. However, mangrove restoration and rehabilitation can bring about a rapid return to fish and invertebrate fisheries, so mangrove nurseries and breeding habitats for fish, crustaceans and mollusc species important to subsistence and or commercial fisheries should be protected. In partnership with local fisher communities, areas should be clearly demarcated for regulated access for non-destructive fishing. Prohibiting fishing within clear defined areas and prohibiting and enforcing destructive fishing practices such as using very fine nets, dynamite and poison should be with full participation and education of local fisher groups.

10.6 Aquaculture

Fish and shrimp aquacultures in mangroves have been carried out for centuries (Ashton 2008) but in the 1960s and 1970s, conversion of mangroves to aquaculture ponds was encouraged in SE Asia (Thailand, Indonesia, the Philippines and Vietnam) to enhance food security and improve livelihoods (Hishamunda et al. 2009). Global shrimp production was 9022 t in 1970 (FAO 2021) but during the 1980s and 1990s, tropical coastal commercial aquaculture had a rapid expansion and displaced 54% of all mangroves that have been lost in Thailand, Indonesia, Vietnam, Brazil, India, Bangladesh, China and Ecuador although there are regional variations (Hamilton 2013). Increasing demand, supply and value of shrimp have led to unsustainable farming practices and large-scale commercial enterprises. Integrated, mixed or mangrove-friendly aquaculture practices with community-based management and stewardships and mangrove rehabilitation are more sustainable for example in Vietnam (Bush et al. 2010) and the Philippines (Primavera 2000). However, the current global market for shrimp is valued at USD 45 billion (FAO 2021), so aquaculture is still a dominant threat to mangrove deforestation especially in Indonesia (Richards and Friess 2016).

As well as the loss of mangroves due to conversion to shrimp farms, there is also a loss of important ecological and socio-economic functions, changes in hydrology, salinisation, introduction of non-native species and diseases and pollution from effluents, chemicals and medicines, use of wild fish for feed, capture of wild shrimp seed and loss of livelihoods and social conflicts (Ashton 2008). There is a removal of

C sequestration capacity and also an increase in C emission as with all clearing of mangroves (Sidik and Lovelock 2013).

Global awareness about the need to reduce the impacts of shrimp farming and the importance of sustainable use of mangrove ecosystems has led to a number of international, national and local guidelines, policies and certification schemes, such as organic or sustainable shrimp (Ashton 2008; Bagarinao and Primavera 2005). No further conversion of mangroves should be allowed for commercial aquaculture and abandoned aquaculture sites should be restored. Critical steps and examples are given by Stevenson et al. (1999). Policies banning mangrove utilisation for shrimp farms are now actively promoted in many countries but they are still not always enforced. Further, awareness raising of consumers in the USA and Europe will drive promotion of ecologically sustainable and socially respectable farmed shrimp (Ashton 2008).

10.7 Agriculture and Mining

Commodities, a combination of shrimp aquaculture and agriculture of rice and oil palm cultivation, were the primary global driver of mangrove loss 47% from 2000 to 2016 and non-productive conversions for petroleum extraction and resource mining caused 12% global mangrove losses (Goldberg et al. 2020). Agricultural expansion for rice production, primarily in Myanmar resulted in 20% mangrove loss from 2000 to 2012 and is expected to continue to be a large threat to mangroves in the future (Richards and Friess 2016). Oil palm plantations are also a continued threat to mangroves especially in Indonesia (Richards and Friess 2016). Sand mining and oil drilling have caused high rates of subsidence in Cameroon and Nigeria, respectively. The negative impacts from mining also include turbidity and siltation of waterways, smothering of mangroves with mining sediments and indirect pollution that can last for many years.

Agriculture is generally unsustainable due to the potential acid sulphate soils in mangrove areas and states should not sanction further conversion of mangroves. Full and independent EIAs should be prepared on existing sites so that changes in hydrology are minimised and there are safeguards against pollution with the polluter pays principle implemented to provide incentives for using appropriate technologies (Macintosh and Ashton 2005).

10.8 Tourism, Recreation and Education

Mangrove ecosystems can provide unique habitats and biodiversity opportunities and have great potential for bird watching, viewing wildlife and scenic boat trips but care should be taken not to allow unplanned and unregulated tourism. To minimise potential, negative environmental impacts from tourism on mangroves tourists should be educated and restricted to clearly defined areas such as board walks. The revenue from ecotourism should be used to pay for the conservation of the mangrove ecosystem. The local communities should be involved in all aspects of tourism development, management and associated activities from the beginning and should also benefit directly by being tourist and boat guides.

Education and awareness raising about mangroves are important at all levels from decision makers in national government agencies, regional officials, private sector, local community and school children. Field visits and workshops are good mechanisms for communities to exchange community experiences in mangrove rehabilitation and conservation. The Mangrove Action Project (MAP) has developed a Mangrove Educational Curriculum for school children from kindergarten to ninth grade in the Cayman Islands, and is taking it to other parts of the world, modifying it for local regions and translating into local languages (https://mangroveactionproject.org/marvellous-mangroves-workshops/).

NGOs, international organisations and academic institutions can all assist in developing and implementing practical training courses to develop regional capacity for sustainable mangrove management and monitoring, such as, the MAP Community-Based Ecological Mangrove Restoration (CBEMR) training services (Mangrove Action Project 2019). Visitor information centres, illustrated information boards, posters, brochures, video, social media and walkways have all been shown to be excellent ways for training and awareness for local visitors for recreation and international tourists.

10.9 Management Shortcomings

Historical causes of mangrove loss stem from lack of awareness, failures in policy, management and enforcement of protection measures. Mangroves being on the land water interface have often not had clear management as a whole ecosystem being assigned on a sectoral basis to government institutions either Forestry, Fishery or Agriculture, which has led to prejudices for objectives, conflicts of interest and unsustainable resource use (Friess et al. 2016; Macintosh and Ashton 2002). These limitations are now recognised and effective, and coordinated policy and legal frameworks supported with clear institutional and administrative responsibilities are understood to be required at local, national and transboundary levels to support mangrove management.

At the international level, there are a number of initiatives, conventions, treaties and agreements that can provide support to nations to sustainably manage and conserve mangroves (e.g. Ramsar Convention on Wetlands, Convention on Biodiversity, World Summit on Sustainable Development, FAO Mangrove Forest Management Guidelines and Code of Conduct for Responsible Fisheries, International Tropical Timber Organisation Mangrove Workplan, Mangrove Charter of International Society for Mangrove Ecosystems, World Heritage Convention, United Nations Framework Convention on Climate Change, Convention on Migratory

Species, Global Mangrove Alliance, etc). Protected area frameworks have been ratified at the national level and enabled mangroves to be protected as Ramsar sites, World Heritage sites, Man and the Biosphere Reserves and Marine Protected Areas. There are also a number of transboundary protected areas, e.g. Sundarbans in India and Bangladesh. Worldwide there are now 2500 protected areas with mangroves, equivalent to 54,000 km^2 or 39% world's remaining mangroves (Worthington and Spalding 2018).

It is important that the remaining 61% of mangroves not currently protected be evaluated. Worthington et al. (2020) provide information on a new platform for visualizing and disseminating datasets to the global science community, NGOs, government officials and rehabilitation practitioners through the Global Mangrove Alliance (GMA). This data is hoped to facilitate collaboration and support policy change that benefits both mangroves and the communities that depend on them. However, some mangroves will remain in private or uncertain ownership with no mechanisms to ensure their long-term future, although Sri Lanka has become a model example by being the first nation to protect all of its mangroves (Chap. 13). Accelerating pressures on coastal areas requires at the national level clear integrated coastal zone management plans and marine spatial planning. Penalties for violations should reflect the severity of the malpractices concerned and speedy disposition of cases involving violations of laws and regulation is strongly urged to protect mangroves resources and deter violators (Macintosh and Ashton 2005). Cross-sectoral coordination, planning and implementation are required which include all involved government departments at all levels, working together with all stakeholders (donor agencies, private, scientific, NGOs and local communities). Where local coastal communities are playing an increasing role in planning and development of mangrove biodiversity conservation and management, successful sustainable management results are found around the world.

The corporate sector also has a role to play through corporate social responsibility (Worthington and Spalding 2018). Payments for Ecosystem Services (PES) or blue carbon hold great promise for mangrove conservation by providing a clear policy objective and incentivizing collaboration (Friess et al. 2016). REDD+ (Reduced Emissions from Deforestation and Forest Degradation) creates a financial value for the carbon stored in forests such as mangroves and could enable countries to receive financial payments for reduced emissions through protection and restoration of mangrove forests (https://www.iucn.org/news/asia/201711/mangroves-and-redd-new-component-mff).

10.10 Conclusions

Mangrove ecosystems continue to be under threat and can be from several different activities simultaneously or over time as land use patterns change. Threats can be localised, regional or global and depend on the location and industries such as urban and industrialisation, forestry, fisheries, aquaculture, agriculture and mining. Off-site activities can also lead to mangrove degradation through siltation or changes in water flow and water quality. Natural threats and increased predicted impacts from global climate change of shoreline erosion, sea level rise and extreme weather events provide further future threats to mangrove ecosystems. Loss of mangroves has led to lost livelihoods, food insecurity and lost coastal defence.

There is now recognition of the value essential ecosystem services such as food provision and coastal protection mangroves deliver (Friess et al. 2016; Liquete et al. 2013). The environmental, social and economic impacts associated with mangrove loss and degradation have been realised and mangrove conservation, restoration and rehabilitation are now being addressed through international agreements, protected areas, integrated policies and planning, reformed government structures, capacity development and environmental education.

The primary goal is to stop the threats and reverse past destruction of mangrove ecosystems but mangrove biodiversity conservation policies cannot succeed unless there is also consideration given to livelihoods. Mangrove restoration and conservation policies must improve food security and livelihood opportunities by providing alternative sources of income for local communities dependent on mangrove resources, and together with the introduction of best practices (ownership and sustainability), and joint planning and management promote sustainable conservation of mangrove biodiversity for the future.

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Part II
Country Case Studies

Chapter 11
Mangrove Forests of India: An Overview

K. Kathiresan

Abstract Mangrove forests of India are globally unique and have the highest record in biodiversity of flora and fauna. India is the second richest country for mangrove biodiversity in the world, with the presence of a "mangrove genetic paradise" in Bhitarkanika, and globally threatened wildlife species in Sundarbans. A vast area of Indian mangrove cover is thriving on the high energy tidal coastal areas of extreme conditions: (i) humid and wet in Sundarbans and (ii) arid and dry in Gujarat. The mangroves are dense, healthy, and biologically diverse along the east coast of India and the Andaman and Nicobar Islands, compared to the west coast. Despite increasing pressures, the Indian mangrove cover is increasing; but, a large tract of the forest has a sparse stand with less canopy density. The Indian mangroves are efficiently managed in 38 selected areas with adequate legal support and participation of stakeholders.

Keywords Mangroves · Biodiversity · Ecosystem services · Conservation · Management

11.1 Introduction

Mangroves are the only tall tree forest, located in the intertidal and estuarine areas of tropical and warm temperate coasts. The mangroves are structurally simple type of forest system with high productivity, and their standing crop is greater than any other aquatic systems on the earth. They are the only blue carbon forest on the earth. The mangroves are an extremophilic ecosystem, capable of surviving in the adverse coastal environment of fluctuating tides, strong winds, high saline, water stress, nutrient-deficient and anaerobic soil conditions. This is possible due to remarkable adaptations to the harsh environment, and no other groups of plants in the entire

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plant kingdom have such adaptations to survive (e.g., Kathiresan and Bingham 2001; Kathiresan and Qasim 2005; Tomlinson 2016; Duke 2017; Kathiresan 2021b).

Mangroves are biodiversity-rich forests due to diversified habitats such as forests, litter-forest floors, mudflats, and water bodies. The Sundarbans provide "home" for globally threatened species such as Royal Bengal tiger, fishing cat, Gangetic dolphin, estuarine crocodile, horseshoe crabs, water monitor lizard, and river terrapins.

Mangroves support fisheries production. In India, the mangrove-rich area provides about 70 times more fish catch leading to a higher income for the fishermen than mangrove-poor areas (Kathiresan and Rajendran 2002). About 60% of Indian coastal and marine fish species are dependent on the mangroves with an estimated yield of nearly two million tons of fish in one million sq.km. Every boat in India gets 25% of fish in the mangrove areas as against only 12% in other areas. Mangroves of India contribute to 23% of commercial marine fisheries output (Lavanya and Kavikumar 2017).

Mangroves are powerful in removing atmospheric CO_2 thereby mitigating the impacts of global warming and climate change (Kathiresan et al. 2013a; Kathiresan et al. 2014; Kathiresan et al. 2021). In India, mangrove forests can remove 96 million tons of atmospheric CO_2 everyday which is equivalent to 386 million US dollars in the international market (Kathiresan 2018a).

Mangrove forests act as a "Green fort for the coast" that offers coastal protection against soil erosion, tsunami, storm surges, cyclone, and floods. The mangrove forests saved thousands of human lives and properties in India during the super cyclone of Odisha in October 1999 and the tsunami of December 2004 (Kathiresan and Rajendran 2005). The coastal protection benefit of a hectare of land with mangroves against cyclone is nearly two times higher than the value of "cleared" land (Das 2004). The mangroves also protect other coastal systems such as islands, seaweeds, seagrass meadows, and coral reefs. Further, the mangroves facilitate sedimentation and strengthen the coastline from soil erosion (Kathiresan and Qasim 2005; Kathiresan 2021b).

Mangroves are of spiritual value. In Sundarbans, the goddess bonabibi (mother of the forests) and her consort Dakshin Rai are worshipped as protectors by both Hindus and Muslims. "Manasa" is worshiped to protect the people from venomous snakes, and "Manik Pir" is invoked for the welfare of cows. In Karnataka, "Kalika Mandir" that is surrounded by dense mangroves is preserved as a sacred shrine by the forest department. A mangrove species (*Excoecaria agallocha*) has been worshiped as a sacred tree at Lord Nataraja temple of Chidambaram in Tamil Nadu dates back to the second century AD. Traditionally, this mangrove species is used as a herbal medicine, and it is scientifically proved for the presence of bioactive chemicals with anti-HIV, anticancer, antiviral, and mosquito-repellent properties. Hence, the mangroves have bioprospecting potential as a source of drugs (Kathiresan 2020).

The mangroves such as *Avicennia marina* have exceptional ability to withstand salt stress and can thrive in salt concentration as high as 90 g per liter. M.S. Swaminathan Research Foundation, Chennai has developed a transgenic paddy crop variety with mangrove genes in the rice genome, which is assessed for biosafety and environmental impact in the field trial. Thus the mangroves have a promise for gene prospecting and in growing food crops along the coastal saline soil for the future.

Globally, mangrove habitats are at an elevated risk of extinction (Polidoro et al. 2010). With growing threats, it is critical to understand the mangrove forests of India for their present status and future actions required for effective conservation and management.

11.2 Extent of Mangrove Cover in India

India has a mangrove forest cover of 4975 sq. km, occupying 3.6% of the global mangroves and 0.15% of total geographical area of India. Sundarbans has the largest mangrove cover, occupying 42.5%, while Gujarat has the second largest cover with 23.7% of total cover in India (SFR 2019). These two areas alone occupy 66.2% of the mangrove cover, thriving in adverse conditions of high energy tidal coast, and experiencing extreme situations. For example, Sundarbans is in humid and wet conditions with high biodiversity, whereas the mangrove forest of Gujarat is in arid and dry conditions with low biodiversity. Interestingly, the Andaman and Nicobar Islands have the third largest mangrove forest of India, occupying 12.4% of the total cover, and located in low energy tidal coasts in humid and wet conditions with rich biodiversity (Kathiresan 2018a).

Mangroves are dense and healthy along the east coast of India and Andaman and Nicobar Islands, compared to the west coast of India. The east coast has 57% of total mangrove cover in India, whereas the west coast has 31% of cover. This variation can be attributed to the mighty rivers (e.g., Ganga, Brahmaputra, Mahanadhi, Krishna, Godavari, and Cauvery) along the east coast that form deltas (Fig. 11.1), rich in sedimentation, upstream water discharge, nutrient-rich alluvial soil, in addition to the smooth topography, which increases the intertidal areas for colonization of mangroves along the east coast. On the contrary, the west coast has narrow intertidal areas due to a steep coast, and absence of deltas as a result of funnel-shaped estuaries. The Andaman and Nicobar Islands have 12.4% of the total mangrove cover, colonizing low energy tidal coasts with accumulation of peat and calcareous materials in coastal fringes, tidal estuaries, small rivers, neritic inlets, and lagoons (Bhatt and Kathiresan 2011; Bhatt et al. 2013).

Forest Survey of India has been assessing the area and extent of mangrove cover using remote sensing techniques since 1987. The 1987 assessment was carried at a scale of 1: 10^6. Since then, the assessment has been continued on a 2-year cycle. The assessment scale was further refined to 1:250,000 from 1989 to 1999 and 1:50,000 from 2001 onwards. There is a general trend of increasing mangrove forest cover in India (Table 11.1; Fig. 11.2).

Indian mangrove cover increased by 54 sq. km. between 2017 and 2019 at 0.55% per year as against global mangroves, which disappear at 0.66%. This cover increase was significant in Maharashtra (5.3%), Odisha (3.29%), and Gujarat (3.25%). There

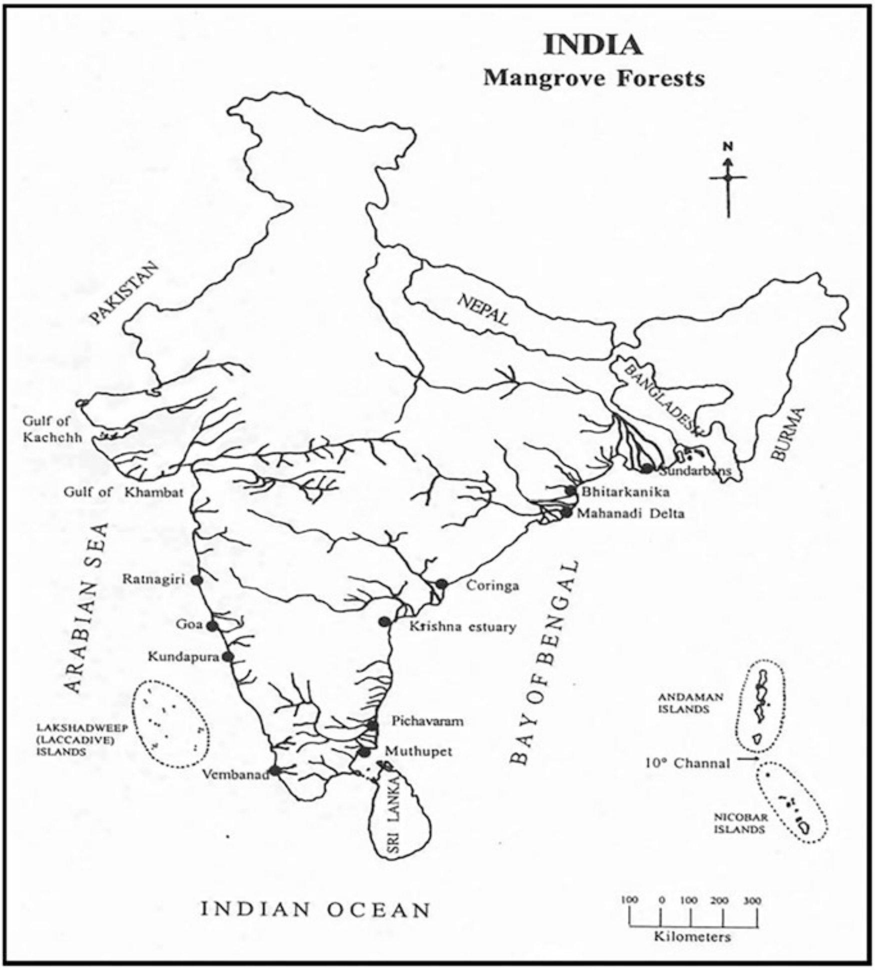

Fig. 11.1 Important locations of mangroves (indicated as closed circles) in different maritime states of India

was a reduction of mangrove cover in Tamil Nadu by 8.2%, Andaman and Nicobar by 0.11%, and West Bengal by 0.09%, while there was no significant change in forest cover in other states/union territories (Table 11.1).

The FSI categorizes the mangrove cover into three types based on the percentage canopy density: very dense (70% and above), moderately dense (40–70%), and open (10–40%). As per the 2019 assessment, the very dense forest occupied 1476 sq km, moderately dense 1479 sq km, and open 2020 sq. km, which are equivalent to 29.6%, 29.7%, and 40.6% of total mangrove cover, respectively. Thus a large track of mangrove forests in India that is 40.6% of total cover has sparse stand with less

Table 11.1 Change of mangrove cover in different maritime states and union territories of India between 2017 and 2019 according to the forest survey of India

	Mangrove forest cover (sq. km)		Change of cover between 2017 and 2019	
	2017	2019	Sq. km	Annual change (%)
Andhra Pradesh	404	404	0	0
Andaman and Nicobar	617	616	−1	−0.08
Gujarat	1140	1177	37	1.62
Maharashtra	304	320	16	2.63
Odisha	243	251	8	1.65
West Bengal	2114	2112	−2	−0.05
Goa	26	26	0	0
Kerala	9	9	0	0
Daman and Diu	3	3	0	0
Karnataka	10	10	0	0
Tamil Nadu	49	45	−4	−4.08
Puducherry	2	2	0	0
Total	4921	4975	54	0.55

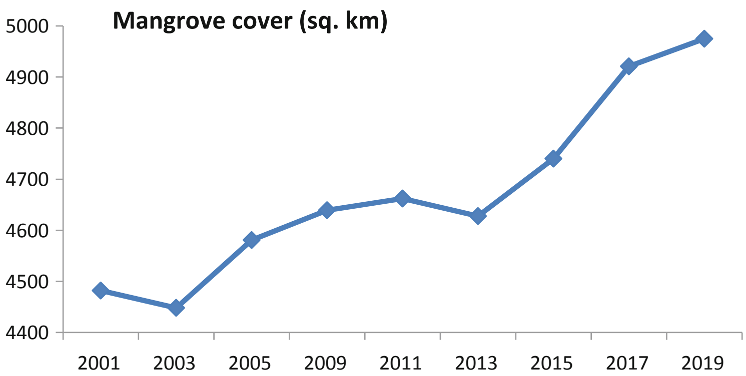

Fig. 11.2 Increasing trend of mangrove cover in India based on the scale of 1:50,000 since the year 2001

canopy density (SFR 2019). This deserves much attention for its transformation into a dense mangrove cover.

11.3 Floral Diversity in Mangrove Forests of India

India is the second richest country for mangrove biodiversity in the world, after Indonesia and Australia (Ragavan 2015; Kathiresan 2019). Bhitarkanika in the Odisha State is considered to be the "mangrove genetic paradise" in the world,

Table 11.2 Number of species, genera, and families of mangroves and mangrove associates in different regions of coastal India

Plant groups	Regions	No. of species	No. of genus	No. of families
Mangroves	East coast	35	19	14
	Andaman and Nicobar Islands	36	18	14
	West coast	25	14	9
	Total	**43**	**19**	**14**
Mangrove associates	East coast	79	7	43
	Andaman and Nicobar Islands	54	49	29
	West coast	55	49	29
	Total	**85**	**73**	**44**
Mangroves + Mangrove associates	East coast	114	84	54
	Andaman and Nicobar Islands	90	5	41
	West coast	80	61	36
	Total	**128**	**90**	**55**

similar to another one in Baimaru of Papua, New Guinea. In the Bhitarkanika, a small island "Kalibhanj dia" is endowed with 101 species of mangroves and mangrove associates along with the largest populations of birds and crocodiles. There are several such areas with rich plant diversity, which should be identified along the country and managed as "Mangrove Germplasm Preservation Centres".

Mangroves are defined as "a tree, shrub, palm or ground fern, generally exceeding one half meter in height, and which normally grows above mean sea level in the intertidal zone of marine coastal environments, or estuarine margins" (Duke Duke 1992, Duke 2017). The "mangrove associates" can be defined as "those of the species that are of either terrestrial or salt marsh origin, which penetrate and adapt to the mangrove habitats. In general, the salt marsh plants occupy high saline regions, whereas the terrestrial plants colonize low to moderate saline regions of the mangrove habitats" (Kathiresan 2019).

There are 43 true mangroves under 19 genera and 14 families; and 85 mangrove associates under 73 genera and 44 families; totally 128 species belonging to 90 genera and 55 families in the mangrove forests of India, based on our extensive field study and literature (Table 11.2). Andaman and Nicobar Islands have higher mangrove species (36 spp.) than that in the east coast (35 spp.) and west Coast (25 spp.), whereas east coast has higher mangrove associates (79 spp.) than Andaman and Nicobar Islands (54 spp.) and west coast (55 spp.). East coast has the maximum number of species of true mangroves + mangrove associates (114 spp.), followed by the Andaman and Nicobar Islands (98 spp.) and west coast (80 spp.) (Table 11.2; Kathiresan 2009, Kathiresan et al. 2013b).

A check-list of true mangroves and associate species is provided in Tables 11.3 and 11.4, respectively. The east coast has 88% of mangrove species, whereas the

Table 11.3 True mangroves occurring along the east and west coasts of India and in Lakshadweep, Andaman and Nicobar Islands

No.	Mangroves	Family	West Bengal	Odisha	Andhra Pradesh	Tamil Nadu	Puducherry	Andaman and Nicobar	Lakshadweep	Gujarat	Maharashtra	Goa	Diu and Doman	Karnataka	Kerala
1	*Acanthus ebracteatus* Vahl	Acanthaceae	–	–	–	–	–	r	–	–	–	–		–	r
2	*Acanthus ilicifolius* L.	,	c	c	f	c		c	–	c	c	c	f	c	c
3	*Avicennia alba* Bl.	Avicenniaceae	c	a	c	–	–	f	–	f	–	–	–	r	–
4	*Avicennia marina* (Forssk.) Vierh.	,	c	f	c	a	c	c	–	a	c	c	f	c	c
5	*Avicennia officinalis* L.	,	c	c	c	c	c	c	–	f	c	c		c	c
6	*Nypa fruticans* Wurmb.	Arecaceae	r	–	–	–		f	–	–	–	–		–	–
7	*Dolichandrone spathacea* (L.f) Schum.	Bignoniaceae	r	r	–	–		c	–	–	r	r		f	c
8	*Cynometra iripa* Kostel.	,	c	c	–	–		r	–	–	r	–		–	–
9	*Lumnitzera littorea* (Jack.) Voigt.	Combretaceae	–	–	–	–		f	–	–	–	–		–	–
10	*Lumnitzera racemosa* Willd.	,	f	c	c	r	r	r	–		c	r		c	r
11	*Excoecaria agallocha* L.	Euphorbiaceae	a	a	a	a	c	f	–	r	a	f		c	c
12	*Barringtonia racemosa*	Lecytidaceae	r	–	–	–	r	–	–	–	r	–	–	–	r
13	*Pemphis acidula* Forst.	Lythraceae	–	–	–	f		c	c	–	–	–		–	–
14	*Sonneratia alba* J. Smith	Sonneratiaceae	–	r	r	–		r	–	–	a	f		c	r
15	*Sonneratia apetala* Buch.-Ham	,	f	f	c	r	r	–	–	r	r	–	r	–	–

(continued)

Table 11.3 (continued)

No.	Mangroves	Family	West Bengal	Odisha	Andhra Pradesh	Tamil Nadu	Puducherry	Andaman and Nicobar	Lakshadweep	Gujarat	Maharashtra	Goa	Diu and Doman	Karnataka	Kerala
16	*Sonneratia caseolaris* (L.) Engl.	,	f	r	–	–		f	–	–	c	c		r	r
17	*Sonneratia griffithii* Kurz.	,	–	–	–	–		r	–	–	–	–		–	–
18	*Sonneratia* x *gulngai* N.C. Duke & Jackes	,	–	–	–	–		r	–	–	–	–		–	–
19	*Sonneratia* x *lanceolata* Bl.	,	–	–	–	–		r	–	–	–	–		–	–
20	*Sonneratia ovata* Backer	,	–	–	–	–		r	–	–	–	–		–	–
21	*Sonneratia* x *urama* N.C.Duke	,	–	–	–	–		r	–	–	–	–		–	–
22	*Brownlowia tersa* (L.) Kosterm.	Malvaceae	c	c	r	–		r							
23	*Heritiera fomes* Buch. –Ham.	Sterculiaceae	r	a	–	–	–	–	–	–	–	–		–	–
24	*Heritiera littoralis* Dryn.	,	–	c	–	–		f	–	–	–	–	–	–	–
25	*Xylocarpus granatum* Koen.	,	c	c	r	r	–	f	–	–	r	–	–	–	–
26	*Xylocarpus moluccensis* (Lam.) M.Roem.	,	f	r	r	r		f							
27	*Aegiceras corniculatum* (L.) Blanco	Myrsinaceae	a	a	f	c	c	c	–	r	c	c	r	r	r
28	*Aegialites rotundifolia* Roxb.	Plumbaginaceae	c	c	r	–		–	–	–	–	–		–	–
29	*Acrostichum aureum* L.	Pteridaceae	c	c	–	r		f	–	–	c	c		c	a

30	*Acrostichum speciosum* Willd.	,	–	r	–	–		r	–	–	–	–		–	–
31	*Bruguiera cylindrica* (L.) Bl.	Rhizophoraceae	c	a	f	c	c	r	r	r	c	r	–	c	c
32	*Bruguiera gymnorrhiza* (L.) Savigny	,	c	c	c	r	r	c	-	r	c	c	–	c	c
33	*Bruguiera parviflora* (Roxb.) W. A. ex Griff.	,	c	r	–	–	–	c	-	–	–	–	–	–	–
34	*Bruguiera sexangula* (Lour.) Poir.	,	f	f	–	–	–	r	–	–	–	–		–	r
35	*Ceriops decandra* (Griff.) Ding Hou	,	c	c	c	c	–	r	–	–	–	–	–	–	–
36	*Ceriops tagal* (Perr.) C.B. Rob.	,	r	r	–	r	c	c	r	r	c	r		r	r
37	*Kandelia candel* (L.) Druce	,	f	a	–	–	–	–	–	r	–	c		c	c
38	*Rhizophora* x *annamalayana* Kathir.	,	–	–	–	r		r	–	–	–	–		–	–
39	*Rhizophora apiculata* Bl.	,	c	r	c	f	f	a	–	–	c	c		r	r
40	*Rhizophora* x *lamarckii* Montr.	,	–	–	–	–		r	–	–	–	–		–	–
41	*Rhizophora mucronata* Poir.	,	c	c	c	f		a	–	r	c	c	–	c	c
42	*Rhizophora stylosa* Griff.	,	–	–	–	–		r	–	–	–	–	–	–	–
43	*Scyphiphora hydrophyllacea* Gaertn.	Rubiaceae	r	–	r	–		c	–	–	–	–	–	–	–
Total number of mangrove species			**28**	**28**	**19**	**17**	**13**	**36**	**3**	**14**	**19**	**15**	**4**	**16**	**17**

Abundant (a) = Species present in 81–100% of sampling points; Frequent (f) = Species present in 61–80% of sampling points; Common (c) = Species present in 31–60% of sampling points; Rare (r) = Species present in 1–30% of sampling points.

Table 11.4 Mangrove associates occurring along the east and west coasts of India and in Lakshadweep, Andaman and Nicobar Islands

No.	Species	Family	West Bengal	Odisha	Andhra Pradesh	Tamil Nadu	Andaman and Nicobar	Gujarat	Maharashtra	Goa	Karnataka	Kerala
Mangrove associate-Trees												
1	*Alphonsea lutea* (Roxb.) Hook.f. & Thoms.	Annonaceae		f		f			f	r	f	
2	*Alphonsea ventricosa* (Roxb.) Hook.f. & Thoms.	"		r			r					
3	*Tamarix indica* Willd.	Tamaricaceae	c	c	c	c	c	c	r			
4	*Calophyllum inophyllum* L.	Clusiaceae	r			r	f				r	r
5	*Thespesia populnea* (L.) Sol. *ex* Correa.	Malvaceae	c	f	f	a	f	c	c	c	c	c
6	*Thespesia populneoides* (Roxb.) Kostel.	"	r	r	r							
7	*Hibiscus tiliaceus* L.	"	c	c	f	a	f		f	f	f	f
8	*Allophyllus cobbe* (L.) Racusch.	Sapindaceae	c	c	c	c			c	c	c	c
9	*Holigarna longifolia* Roxb.	Anacardiaceae	–	r	r	r						
10	*Pongamia pinnata* (L.) Pierre	Fabaceae	c	c	r	r	f		r	c	c	r
11	*Barringtonia asiatica* (L.) Kurz.	Barringtoniaceae					r					
12	*Ixora arborea* Roxb. *ex* Sm.	Rubiaceae	f	f	f	f			f	r	f	

13	*Manilkara littoralis* (Kurz.) Dubard	Sapotaceae					c					
14	*Diospyros malabarica* (Desr.) Kostel.	Ebenaceae	r	r	r	r	r	r	r	r	r	r
15	*Salvadora persica* L.	Salvadoraceae		c		r		c				
16	*Cerbera manghas* L.	Apocyanaceae	r	r			f				c	r
17	*Cerbera odollum* Gaertn.	"		r					r		c	c
18	*Premna latifolia* Roxb.	Verbenaceae				f			f	r	f	
19	*Premna serratifolia* L.	"				f	f	f	f	r	f	
20	*Antidesma ghaesembilla* Gaertn.	Euphorbiaceae	r	r	r	r	r	r	r	r	r	r
21	*Excoecaria indica* (Willd.) Mull.Arg.	"	r				r					
22	*Ficus microcarpa* L.f.	Moraceae	f	f	f	f					f	f
23	*Ficus virens* Dryan.	"	f	f		f					f	
24	*Pandanus odoratissimus* Roxb.	Pandanaceae	c	c	c	c	c		r	r	r	r
25	*Pandanus tectorius* Soland. *ex* Park.	"	c	r	c	r	c					
26	*Aglaia cuculata* (Roxb.) Pelleg.	Meliaceae	r	r								
27	*Phoenix paludosa* Roxb.	Arecaceae	c	c			c					
28	*Intsia bijuga* (Colebr.) O. Kuntze	Caesalpiniaceae	c	r			r					
29	*Cynometra ramiflora* L.	"					r					

(continued)

Table 11.4 (continued)

No.	Species	Family	West Bengal	Odisha	Andhra Pradesh	Tamil Nadu	Andaman and Nicobar	Gujarat	Maharashtra	Goa	Karnataka	Kerala
Mangrove associate- Shrubs												
1	*Capparis decidua* (Forsskal) Edgew	Capparaceae					f					
2	*Acanthus volubilis* Wall.	Acanthaceae	r				r					
3	*Merope angulata* (Willd.) Swingle	Rutaceae	r	r								
4	*Maytenus emarginata* (Willd.) Ding Hou.	Celastraceae	r	r	r	r	r	r	r	r	r	r
5	*Colubrina asiatica* (L.) Brong.	Rhamnaceae		f								
6	*Lepisanthes tetraphylla* (Vahl) Radlik	Spindaceae		f	f		f		f		f	
7	*Indigofera tintoria* L.	Fabaceae	r	r	r	r	r	r	r	r	r	r
8	*Dalbergia spinosa* Roxb.	"	c	c	c	c						
9	*Derris scandens* (Roxb.) Benth.	"	c	r	c		f		c	c	c	r
10	*Derris trifoliata* Lour.	"	c	c	f	c	c		c	c	c	c
11	*Caesalpinia crista* L.	Caesalpiniaceae	c	c	f	c	c		c	c	c	c
12	*Caesalpinia bonduc*(L.) Roxb.	"	c	c	f	r	f		c	c	c	r
13	*Parkinsonia aculeata* L.	"	r	r	r	r	r	r	r	r	r	r

14	*Pluchea indica* (L.) Less.	Asteraceae	c				r					
15	*Carissa paucinervia* L.	Apocyanaceae	c	c	c	c			c	r	c	
16	*Finlaysonia obovata* Wall.	Periplocaceae	r	r			c					
17	*Sarcolobus carinatus* Wall.	Asclepiadaceae	c	c	c		c					
18	*Sarcolobus globosus* Wall.	"	c	r	c		r					
19	*Tylophora tenuis* Bl. Bijolr.	"	f	r			c					
20	*Clerodendrum inerme* (L.) Gaertn.	Verbenaceae	c	c	c	c	c	r	c	c	c	C
21	*Vitex trifolia* L.	"	f						c	f	f	f
22	*Bridelia stipularis* (L.) Bl.	Euphorbiaceae	r	r	r	r	r	r	r	r	r	r
23	*Jatropha curcus* L.	"	r	r	r	r	r	r	r	r	r	r
24	*Phyllanthus reticulatus* Poir.	"	f	f	f	f	f					
Mangrove associate-Herbs												
1	*Heliotropium curassavicum* L.	Boraginaceae	r	r	c	c		c	c	c	r	r
2	*Salacia chinensis* L.	Hippocrateaceae	c	c	c	c	r					
3	*Desmodium biarticulatum* (L.) Muell.	Fabaceae		c	c	c						c
4	*Vigna marina* (Burm. f.) Merr.	Aizoaceae					c					

(continued)

Table 11.4 (continued)

No.	Species	Family	West Bengal	Odisha	Andhra Pradesh	Tamil Nadu	Andaman and Nicobar	Gujarat	Maharashtra	Goa	Karnataka	Kerala
5	*Sesuvium portulacastrum* (L.) L.	"	r	r	c	c	f	c	r	r	r	r
6	*Sphenoclea zeylanica* Gaertn.	Spenocleaceae		r		r						
7	*Centranthera tranquebarica* (Spreng.) Merr.	Scorphulariaceae	c	c	c	c		c	c	r	c	
8	*Allmania nodiflora* (L.) R.Br. *ex* Wight	Amaranthaceae	f	f	f			f	f	r	f	
9	*Suaeda nudiflora* (Willd.) Moq.	Chenopodiaceae	r	r	c	c						
10	*Suaeda monoica* Forsk.*ex* Gmel.	"	r	r	c	c						
11	*Suaeda maritima* (L.) Dum	"	r	r	a	a		c	r			
12	*Suaeda fruticosa* (L.)	"			c	c		c				
13	*Salicornia brachiata* Roxb.	"	r	r	c	a	r	c	r	r	r	r
14	*Basella alba* L.	Basellaceae	f	f	f	f			f	r	f	
15	*Scurrula philippensis* (Cham. & Schlt.) G. Don.	Locanthaceae		f		f						
16	*Cryptocoryne ciliata* (Roxb.) Schott.	Arecaceae	c	c								

17	*Fimbristylis ferruginea* (L.) Vahl	Cyperaceae	c	c	a	a	c	a	c	c	c	c
18	*Myriostachya wightiana* (Nees *ex* Steud.) Hook.f.	Poaceae	c	f	a	a	r					
Mangrove associate-Climbers												
1	*Cayratia trifolia* (L.) Domin.	Vitaceae		c	c	r			c	c	c	c
2	*Mucuna gigantea* (Willd.) DC.	Fabaceae	c	c			c					c
3	*Cucumis callosus* (Rottl.) Cogn.	Cucurbitaceae	r	r	r	r	r	r	r	r	r	r
4	*Ipomoea tuba* (Schld.) G. Don.	Convolvulaceae		c	a	a		a				r
5	*Flagellaria indica* L.	Flagellariaceae	c	c			f		c	c		c
6	*Stenochlaena palustre* Bedd.	Pteridaceae		c			f					
Mangrove associate-Grasses												
1	*Aeluropus lagopoides* (L.)Trin. *ex.* Thw.	Poaceae	r		c	c		r				
2	*Porteresia coarctata* (Roxb.) Tateoka	"	c	c	c	c	c	c	c	c	c	
3	*Sporobolus virginicus* (L.) Kunth.	"					r		r			r
4	*Urochondra setulosa* (Trin)Hubh.	"						r				
Epiphytes												
1	*Dischidia numularia* R.Br.	Asclepiadaceae					c					

(continued)

Table 11.4 (continued)

No.	Species	Family	West Bengal	Odisha	Andhra Pradesh	Tamil Nadu	Andaman and Nicobar	Gujarat	Maharashtra	Goa	Karnataka	Kerala
2	*Hoya parasitica* Wall.	”	r	r	r	r	r					
Mangrove associate- Parasites												
1	*Dendrophthoe falcata* (L.f.)	Loranthaceae	r	r	r	r	r	r	–	–	–	–
2	*Viscum ovalifolium* Willd.						r					
Total number of mangrove associates			**60**	**68**	**51**	**53**	**54**	**27**	**41**	**36**	**40**	**34**

Abundant (a) = Species present in 81–100% of sampling points; Frequent (f) = Species present in 61–80% of sampling points; Common (c) = Species present in 31–60% of sampling points; Rare (r) = Species present in 1–30% of sampling points.

Table 11.5 Number of true mangroves, mangrove associates, and total in mangrove forests of different states/union territories of India

Maritime State/Union Territories	No. of species in mangrove habitat		
	True mangroves	Mangrove associates	Total mangrove species
West Bengal	28	60	88
Odisha	28	68	96
Andhra Pradesh	19	51	70
Tamil Nadu (including Puducherry)	17	53	70
Andaman and Nicobar Islands	36	54	90
Gujarat	14	27	41
Maharashtra	19	41	60
Goa	15	36	51
Karnataka	16	40	56
Kerala	17	34	51

west coast has 62% of mangrove species (Kathiresan 2019). This variation in species diversity can be attributed to the favorable conditions for colonization of mangrove species. The east coast is endowed with large intertidal areas and presence of nutrient-rich deltas, whereas the west coast has narrow intertidal areas and absence of deltas. The Andaman and Nicobar Islands have 75% of mangrove species, due to habitat diversity such as coastal fringes, tidal estuaries, small rivers, neritic inlets, and lagoons (Bhatt and Kathiresan 2011; Bhatt et al. 2013).

Plant diversity is the highest in Odisha (96 spp.) followed by Andaman and Nicobar Islands (90 spp.), and Sundarbans in West Bengal (88 spp.), whereas it is the lowest in Gujarat (41 spp.). Mangrove associates exhibit much greater diversity than true mangroves. True mangrove species are in a range from 14 (Gujarat) to 36 (Andaman and Nicobar Islands), whereas mangrove associates vary between 27 (Gujarat) and 68 (Odisha) (Table 11.5).

In India, 16 true mangroves and seven mangrove associates are of rare occurrence and restricted in distribution (Table 11.6). According to IUCN Red List, 11 mangrove species are at high threat of extinction in the world, out of 70 species excluding hybrids assessed. India has two globally threatened species, and they are critically endangered *Heritiera fomes* and endangered *Sonneratia griffithii* (Kathiresan 2010; Polidoro et al. 2010). These two species are nearing local extinction due to low-seed viability and slow growth. *Sonneratia griffithii* is present only in Andaman and Nicobar Islands, whereas *Heritiera fomes* is present in Bhitarkanika (Odisha) and Bangladesh border of Indian Sundarbans, and this species is locally known as "Sundari" that means beautiful species. In Sundarbans, freshwater loving species such as *Heritiera fomes* and *Nypa fruticans* have reduced in population density as a result of reduced freshwater inputs (Kathiresan 2010, 2019).

Some mangrove species are restricted in occurrence and distribution in India (Table 11.6). *Pemphis acidula* is restricted to coral islands. The mangrove palm

Table 11.6 Mangroves of rare occurrence and restricted distribution in India

	Name of species	State of occurrence
Mangroves		
1	*Acanthus ebracteatus*	Andaman, Kerala
2	*Lumnitzera littorea*	Andaman
3	*Nypa fruticans*	West Bengal, Andaman
4	*Rhizophora x annamalayana*	Tamil Nadu, Andaman
5	*Rhizophora stylosa*	Odisha and Andaman
6	*Rhizophora* x *lamarckii*	Andaman
7	*Schphiphora hydrophyllacea*	West Bengal, Andhra Pradesh, and Andaman
8	*Sonneratia griffithii*	Andaman
9	*Acrostichum speciosum*	Andaman and Odisha
10	*Heritiera fomes*	West Bengal, Odisha
11	*Sonneratia lanceolata*	Andaman
12	*Sonneratia ovata*	Andaman
13	*Sonneratia* x *urama*	Andaman
14	*Sonneratia* x *gulngai*	Andaman
15	*Brownlowia tersa*	West Bengal,Odisha,AndhraPradesh
16	*Xylocarpus moluccensis*	Odisha, Andhra Pradesh, and Andaman Maharashtra
Mangrove associates		
1	*Merope angulata*	West Bengal, Odisha
2	*Phoenix paludosa*	West Bengal, Odisha, and Andaman
3	*Aglaia cucullata*	West Bengal, Odisha
4	*Excoecaria indica*	Andaman, West Bengal
5	*Tylophora tenuis*	West Bengal,Odisha,AndhraPradesh
6	*Urochondra setulosa*	Gujarat, Maharashtra
7	*Thespesia populneoides*	West Bengal, Odisha, and Andhra Pradesh

N. fruticans is restricted to Andaman and Nicobar Islands and Sundarbans. *Scyphiphora hydrophyllacea* occurs only in Krishna and Godavari estuaries, Sundarbans, and in Andaman and Nicobar Islands. The fern *Acrostichum speciosum* is found only in Odisha and in Andaman and Nicobar Islands. *Brownlowia tersa* has patchy distribution in Sundarbans, Odisha, and east Godavari district as well in Andaman Islands (Kathiresan et al. 2013b). *Brownlowia tersa,* reportedly growing abundant nearer to large creeks of the Middle Andamans and Dhanikhari creek some 80 years ago, is now rarely observed there (Hajra et al. 1999). Eight mangrove species are recorded only in Andaman and Nicobar Islands, and these are *Lumnitzera littorea*, *Rhizophora* × *lamarckii*, *Rhizophora* × *mohanii*, *Sonneratia* × *urama*, *Sonneratia* × *gulngai*, *Sonneratia griffithii*, *S. lanceolata,* and *S. ovata* (Ragavan 2015).

In Sundarbans, the population of *Nypa fruticans* and *Heritiera fomes* is reduced due to the reduction in freshwater inputs. *Xylocarpus* species is becoming rare in the

Table 11.7 Floral species diversity reported in the mangrove forest ecosystems of India

No.	Floral group	No. of species
1	Mangroves	43
2	Mangrove-associated land plants	85
3	Seagrasses	11
4	Marine algae	557
5	Bacteria	69
6	Fungi	103
7	Actinomycetes	23
8	Lichens	32
	Total	**923**

Sundarbans due to past over-exploitation (Naskar and Mandal 1999). *Rhizophora annamalayana* is a rare mangrove species in India, identified first from Pichavaram mangrove in south east India (Kathiresan 1995, 1999). It is a natural hybrid derived from two parental species - *R. mucronata* and *R. apiculata* - taxonomically erected by Kathiresan (1999), and confirmed by using DNA markers (Parani et al. 1997). This critically endangered hybrid finds place in the global list of mangrove species (FAO 2007). Occurrence of this species has recently been reported from Andaman Islands (Ragavan 2015) as well in Sri Lanka.

Heritiera kanikensis was reported to be a new species that exists only in Bhitarkanika of Odisha (Majumdar and Banerjee 1985), but our field visits to the study site at Bhitarkanika, and re-examination of the field and herbarium specimens at Botanical Survey of India, Kolkata reveal that the species is *Heritiera fomes,* not a new species.

In addition to 43 true mangroves and associated land plant species, there are other floral groups namely seagrasses, marine algae, bacteria, fungi, actinomycetes, and lichens found to be present in the mangrove ecosystems of India (Table 11.7). Total number of floral species are 923, of which marine algae and fungi are predominant with high species diversity of 557 and 103 species, respectively (Kathiresan 2018a, 2019).

11.4 Faunal Diversity in Mangroves of India

Sundarbans supports a rich faunal diversity. Hence, it is internationally recognized as a World Heritage Site of UNESCO. The Sundarbans in India and Bangladesh put together is the largest mangrove forest, and it is also the only mangroves in the world, colonized by the Royal Bengal Tiger. This is a dense mangrove forest, unique to have the flora and fauna amazingly adjusted to the rigorous ever-fluctuating tidal environment. Other natural treasures along the mangroves of India are: (i) the world's largest nesting site for the Olive Ridley turtle in Gahirmatha coast of Odisha; (ii) seagrass meadows associated with the sea cow (Dugong); (iii) coral reefs

Table 11.8 Number of faunal species reported in the mangrove forest ecosystems of India

No.	Faunal group	No. of species
1	Protozoa (Protista)	349
2	Cnidaria	73
3	Rotifera	53
4	Nematoda (free living)	125
5	Polychaeta	244
6	Oligochaeta	21
7	Arachnida	309
8	Crustacea	624
9	Insecta (Insects)	1422
10	Mollusks	173
11	Other minor groups	84
12	Tunicata (Urochordata)	6
13	Fin fish (Pisces)	659
14	Amphibians	14
15	Reptilia (Reptiles)	57
16	Birds (Aves)	523
17	Mammals	86
	Total faunal species	**4822**

associated with ornamental fishes; and (iv) intertidal mudflats teeming with migratory and residential birds (Kathiresan and Qasim 2005).

The Indian mangrove ecosystem has most of the groups of animal communities,17 core phyla from the lowest phylum of Protozoa to the advanced phylum Mammalia (Table 11.8). There are a total of 4822 species of animals, which contribute about 4.76% of Indian fauna. The groups that are dominant with >100 species are in decreasing order insects, finfish, crustacea, birds, protozoa, arachnida, polychaeta, mollusks, and nematodes (Kathiresan 2000b, 2009, 2018a; Kathiresan et al. 2015; Chandra et al. 2019).

India's rich faunal diversity is distributed differently along the East coast, Andaman and Nicobar Islands and West coast of India. Of the total of 4822 faunal species, the east coast is represented with 82% (3939 species), followed by West coast with 38% (1837 species), and the Andaman and Nicobar Islands with 23% (1093 species) (Table 11.9). Mangrove habitat characteristics play a role in the faunal species diversity.

Many mangrove-associated faunas are at threat as per IUCN categorization. In the Sundarbans, four reptile, three bird, and five mammal species are extinct (Table 11.10), while ten reptile, three bird, and two mammal species are at threat (Table 11.10; Chaudhuri and Choudhury 1994). In Gujarat, three bird and two turtle species are at threat (Table 11.11; Sunderraj and Serebiah 1998). Of the 41 invertebrates assessed in India, four species are endangered, four vulnerable, and one critically endangered. Of the 52 species of marine fish assessed in the country, nine are vulnerable and two endangered (Rao et al. 1998; Table 11.12).

Table 11.9 Faunal species diversity reported in different regions of Indian mangrove ecosystems

Faunal group	No. of faunal species			
	East coast	Andaman and Nicobar Islands	West coast	Total
Protozoa (Protista)	266	23	107	349
Cnidaria	52	1	19	73
Rotifera	53	0	2	53
Nematoda (free living)	85	36	14	125
Polychaeta	234	8	85	244
Oligochaeta	16	3	19	21
Arachnida	246	8	88	309
Crustacea	402	77	198	624
Insecta (Insects)	1176	268	367	1422
Mollusks	127	100	85	173
Other minor groups	71	23	32	84
Tunicata (Urochordata)	3	2	2	6
Fin fish (Pisces)	623	284	388	659
Amphibians	14	4	0	14
Reptilia (Reptiles)	53	18	0	57
Birds (Aves)	440	226	359	523
Mammals	78	12	72	86
Total faunal species	3939	1093	1837	**4822**

11.5 Drivers and Pressures

Mangrove forests continue to be stressed by various pressures, such as habitat conversion for urbanization, aquaculture, agriculture, salt farming, and other developmental activities. Other stressors are tourism, mining, refineries, oil pipeline passages, port/harbor, dam and road constructions, changes in hydrological regimes, increasing salinity, coastal pollution, siltation, over-exploitation of fishery resources, cattle grazing, private ownership, and ineffective institutional regimes (Kathiresan 2018a).

Specific stressors in India are: (i) agriculture and prawn seed collection in the Sundarbans, West Bengal, (ii) prawn farming and encroachment in Andhra Pradesh and Odisha, (iii) cattle grazing in Tamil Nadu and Gujarat, (iv) industrial developments in Gujarat, (v) cyclone and floods along the east coast, (vi) mangrove areas under private lands in Kerala, Maharashtra, and Karnataka, and (vii) urbanization in Mumbai (Bhatt et al. 2013).

Climate change is a growing natural threat, especially sea level rise in low lying coastal areas of the country. Coastal erosion as driven by sea level rise is another growing threat. Mangrove habitats of the east coast have a smooth slope, while the west coast except Kerala has a steep slope. Hence, the east coast of India and Kerala is vulnerable to sea level rise and coastal erosion, compared to other areas (Kathiresan 2017, 2018b). Coastal erosion is the highest in West Bengal followed by Pondicherry, Kerala, Gujarat, Tamil Nadu, Karnataka, Maharashtra, Odisha,

Table 11.10 Threatened and extinct species of reptile, bird, and mammal in the Sundarbans

No.	Species	Family	No.	Species	Family
Reptiles					
1	*Crocodilus porosus*	Crocodilidae	8	*Caretta caretta*[a]	Chelonidae
2	*Varanus bengalensis*	Varanidae	9	*Dermochelys coriacea*[a]	Chelonidae
3	*V. salvator*	Varanidae	10	*Lissemys punctata*	Trionychidae
4	*V. flavescens*	Varanidae	11	*Trionyx gangeticus*	Trionychidae
5	*Chelonia mydas*[a]	Chelonidae	12	*T. hurun*	Trionychidae
6	*Eretmochelys imbricata*[a]	Chelonidae	13	*Batagur baska*	Emydidae
7	*Lepidochelys olivacea*	Chelonidae	14	*Python molurus*	Boidae
Birds					
1	*Pelecanus philippensis*	Pelecanidae	4	*Ardea goliath*	Ardeidae
2	*Theskiornis melanocephalus*	Threskiornithidae	5	*Sarkiodornis melanotus*[a]	Anatidae
3	*Leptoptilos javanicus*[a]	Ardeidae	6	*Cairina scutulata*[a]	Anatidae
Mammals					
1	*Panthera tigris*	Felidae	5	*Cervus deruchea*[a]	Cervidae
2	*Muntiacus muntjac*[a]	Felidae	6	*Axis porcinus*[a]	Cervidae
3	*Bubalis bubalis*[a]	Felidae	7	*Platanista gangetica*	Platinistidae
4	*Rhinoceros sondaicus*[a]	Felidae			

[a] Extinct species

Table 11.11 Threatened bird and turtle species in the mangroves of Gujarat

No.	Species	Family
1	*Platelia leucorodia*	Threskiornithidae
2	*Pelecanus philippensiscrispus*	Pelecanidae
3	*Pelecanus philippensis*	Pelecanidae
4	*Chelonia mydas*	Chelonidae
5	*Lepidochelys olivacea*	Chelonidae

Andhra Pradesh, and Goa. The hot spots of coastal erosion are Sagar Island in West Bengal, Kendrapada and Puri districts of Odisha, Diu, Pondicherry, Mumbai city, Alappuzha district of Kerala (Ramesh et al. 2018).

After the 2004 tsunami, coastal soil salinity increased along the east coast of India, and this is a likely cause for changes in the floral composition and benthic organisms in the mangrove soils (Kathiresan 2000a; Sandilyan et al. 2010). Furthermore, the Bay of Bengal is a breeding site of cyclones and storms that frequently affect Odisha, Andhra Pradesh, West Bengal, and Tamil Nadu. Some area-specific stressors are discussed for different regions of India.

Table 11.12 Threatened species of invertebrates and marine fish in the mangrove ecosystems of India

No.	Species	Family
Invertebrates		
1	*Cardisoma carnifex****	Gecarcinidae
2	*Gelonia erosa***	Geloindae
3	*Uca tetragonon***	Ocypodidae
4	*Macrophthalamus convexus***	Ocypodidae
5	*Pilodius nigrocrinitus***	Xanthidae
6	*Sesarma taeniolata**	Grpsidae
7	*Penaeus canaliculatus**	Palaemonidae
8	*Penaeus japonicus**	Palaemonidae
9	*Meretrix casta**	Veneridae
Marine fish		
1	*Boleophthalmus dussumieri***	Gobiidae
2	*Scartelaos viridis***	Gobiidae
3	*Arius subrostratus*	Ariidae
4	*Psammaperca waigaensis*	Centropomidae
5	*Elopes machnata*	Elopidae
6	*Boleophthalmus boddarti*	Gobiidae
7	*Periophathalmus koelreuteri*	Gobiidae
8	*Leiognathus splendens*	Leiognathidae
9	*Secutor ruconius*	Leiognathidae
10	*Muraenichthys schultzei*	Muraenidae
11	*Desyatis uarnak*	Trygonidae

***Extinct species, **Endangered, *Vulnerable

11.5.1 Sundarbans, West Bengal

Erosion and accretion are the two natural processes that take place in different parts of the Sundarbans. The southern and western parts of the islands are most prone to erosion, while eastern and northern parts are experiencing accretion. After the operation of the Farakka Barrage, the freshwater flow reduced from the Ganga into the Sundarbans, and hence many parts of the Sundarbans are silted up, hindering navigation and altering the basic physical processes. Siltation is a problem, especially in Haldia Port. The port authorities have developed mangroves in the Nayachara Island, nearer to the port in order to deepen the area.

Erosion is an issue along the estuarine mouths due to severe tidal wave action. The erosion of embankments results in flooding of human dwellings, which is a perennial problem especially during the monsoon in the Sundarbans. The Indian Sundarbans have lost 3.71% of mangrove and other forest cover, and 9990 ha of landmass due to erosion in one decade according to satellite analysis by ISRO (The Hindu, March 9, 2015). In Sagar Island in 1985, the mean sea level was 2.6 mm/year, this increased to 4 mm/year in 2010 that resulted in coastal erosion, coastal flooding, and an increase in the number of tidal creeks. There is less freshwater flow and reduced sediment supply in the western Indian part of the Sundarban delta, and the rate of sea level rise is higher than sediment supply. In the Sundarban Tiger Reserve, the loss of island area due to sea level rise is less significant as compared to the impact of increasing salinity on the mangrove vegetation. Though the southernmost islands of Mayadwip block are directly impacted by the ocean current, the rate of erosion of land area in the southern zone is much less as compared to that in the central and northern parts of the Tiger Reserve. This is due to the higher rate of accretion due to sediment flow with the ocean current and its deposition on the islands during high tides, resulting in faster degradation of mangrove vegetation in the western, northern, and central zones of the Tiger Reserve.

Freshwater loving species of mangroves are replaced by salt-water loving ones. For example, the populations of sundari trees (*Heritiera fomes*) have reduced, while the number of high salt-tolerant *Avicennia* species have increased (The Hindu, September 7, 2014; November 23, 2014). Illegal felling is a threat to *Xylocarpus granatum* for its medicinal use in the treatment of cholera, diarrhea, and fever. *Ceriops decandra* and *Avicennia* are collected for supplementing fuel wood requirements by residents. Among 12 orchid species reported in the past from the Sundarbans, most of them can no longer be observed (The Hindu, February 18, 2018).

The Sundarbans is inhabited largely by very poor people, lying below the poverty line. About 94.6% of the total population depends on agriculture; of which, more than 54% do not own any land and they work as landless laborers. The remaining 5.4% of the population is engaged in fishery, forestry, and handicrafts. There is over-dependence of the people upon natural resources leading to illegal harvesting of natural resources within the biosphere region. The illegal exploitation of timber products, wildlife, fisheries including juvenile shrimps is a major problem (Mitra and Bhattacharyya 2001). The people, especially women, are involved in collection of the juvenile tiger shrimp for aquaculture practices. During this operation, other fish juveniles are killed. About 48 to 62 species of finfish juveniles are wasted per net per day. Annually, a single haul may destroy 17,947 tons of other fish juveniles. Undersized fishes are harvested, and other fishes at their reproductive stages are over-fished using nets of small mesh size (Mitra and Kakoli 2005). Fish and prawn seed resources are largely destroyed in the Hooghly-Matlah estuarine system of the Sundarbans (Das et al. 1987). The prawn catch activity may also spoil the stability of peripheral regions of the banks. Further, salinity has gone up by 20% in the Sundarbans since 1990. Due to this high salinity, the fish species of high commercial values are replaced by those that do not have much market value, and thus the fishermen suffer due to lack of fish catch (The Hindu, July 2, 2017). The present flow of freshwater in the Sundarbans is insufficient to maintain the ecosystem from degradation, and it requires 507 cubic meters per second of freshwater in the lean period (The Hindu, November 23, 2014).

A majority of residents of the Sundarbans lack access to drinking water, roads, and proper health care facilities. They are vulnerable to diseases such as malaria, diarrhea, skin, and fungal infections. The absence of family planning measures and unchecked cross border infiltration has resulted in population increase. The population within Indian boundaries has risen from 1.15 million in 1951 to 4.4 million after six decades. The population density of Indian Sundarbans outside the tiger reserve area is 1000 per sq. km and there is an incidence of high malnutrition problem (The Hindu, April 13, 2008).

There are incidents of man-animal conflicts. Despite warnings to local people not to venture into the waters, particularly at night, women frequently go to the rivers to collect prawn and they get attacked by crocodiles. Deer meat is often served at wedding feasts, and hence, hunting for deer does occur. Over the years, the biosphere's delicate balance has been upset because of shrinking habitats and poaching. This in turn, has escalated man-animal conflicts. Awareness on this aspect is created among children though nature clubs in 22 schools on Bali Island (The Hindu, April 13, 2008).

The "Project Tiger" program conserves the population of the endangered tigers. However, killing of tigers outside the reserve forests occurs sometimes by trapping the tigers using the cattle prey poisoned with endosulphan. The forest department has established bamboo fences covered with nylon along the forest to prevent the entry of tigers into the villages. However, 25 tigers strayed into Sundarbans villages and injured around a dozen people during 2009 and 2010. The tigers are adapted to drink saline water due to decreased availability of freshwater (The Hindu, June 5, 2006). However, three tigers are killed annually. The tigers are living mostly along the periphery of mangrove islands, and these areas are vulnerable to sea level rise. Hence, it is believed that the entire population of over 100 tigers will be lost within 50 years by 2070 due to loss of their habitats (Mukul et al. 2019).

Rising sea levels and subsequent loss of land may contribute to more than 10,000 environmental refugees struggling for survival in the Sundarbans (The Hindu, February 24, 2008). Sea level rise is increasing at an average rate of 3.14 cm a year over the past two decades. This has resulted in two islands (Lohachara and Suparibhanga) being submerged and Ghoramara Island losing 50% of its land mass, thus displacing hundreds of people from their homes and having to find shelter in the four refugee colonies in adjoining Sagar Island (The Hindu, June 5, 2006).

Globally the present rate of sea level rise is 3–4 mm/year, but the projected sea level rise may exceed 10 mm/year by 2100. If it exceeds 6–7 mm/year, the mangroves cannot develop, but in many mangrove locations, rates of relative sea level rise are already higher than 6–7 mm/year. Subsidence of coastal land is caused by extraction of oil, gas, and water. For example, the Mekong Delta of Vietnam is subsiding at a rate of 6–20 mm/year and the Ganges-Brahmaputra Delta by 1–7 mm/year, accompanied by land erosion and saltwater intrusion. At the same time, the sediment supply to the coast has declined due to dam constructions across the rivers or sediment mining and export in some cases. Global mangroves may be unable to initiate suspended accretion when sea level rise exceeds 6.1 mm/year. This threshold may surpass beyond 7 mm/year sea level rise on tropical coastlines within 30 years by 2050, and the mangroves may fail to develop (Lovelock 2020).

A major concern is the quantity of polluted water entering the Sundarbans from outside, in particular, human sewage from Kolkata. Pollution due to heavy discharge of effluents from many factories has spoiled the water resources (Chaudhuri and Choudhury 1994). The Sundarbans has long been declared as a plastic-free zone;

yet, it is dumped with plastic waste in the form of plastic covers, cups, and wrappers. The pollution poses an ecological hazard for both flora and fauna (The Hindu, June 10, 2009).

11.5.2 Odisha

Odisha mangroves have a serious problem of encroachments. Refugees from Bangladesh migrated there in 1962 and encroached the forest lands for inhabitation and agriculture practices. Aquaculture in the area had created resentment among the local fishermen. An area of 8502 acres was encroached by aquafarms, 7690 acres in Mahanadhi deltas, and 811.84 acres in Bhitarkanika. A large area of mangroves were cleared in the Hatamundia Reserve forest for aquaculture purposes (ISRO 1992). About 3000 ha were cleared nearer to Karanjamal and Paradip Port at the mouth of Mahanadhi River. About 20 villages in Mahanadhi area and 59 villages in Bhitarkanika depend on mangroves for their livelihood. Most of their houses are constructed by using mangroves. *Phoenix* stems are used for construction of walls and leaves for thatching, whereas *Heritiera, Lumnitzera, Xylocarpus,* and *Avicennia* are used for making doors and windows (Chadha and Kar 1999).

Forest resources are under pressure for fodder due to a large cattle population. This is a problem specifically after the harvest of agriculture crops, when the people are unemployed during the period between December and May. An estimated 70,000 cattle are found within the sanctuary. During cropping season, from June to November, these cattle depend mainly on the forests for fodder. *Avicennia*, an excellent fodder is under intense pressure due to heavy grazing by buffaloes in Bhitarkanika, Mahanadhi Delta, Balasore coast, and Jagatshinghpur district (Chadha and Kar 1999).

The construction of a dam on Brahmani at Rengali at 220 km upstream has diminished the availability of fresh water and silt in the mangrove estuarine regions of Bhitarkanika. The progressive reduction of sedimentation due to dam construction can pose a threat to new colonization of mangroves (Rao and Das 2007).

11.5.3 Andhra Pradesh

Siltation is a major problem. For example, Kakinada Bay has only about 1.5 m depth at high tides, due to heavy siltation, which may result in the changes of water movements and in the formation of mudflats. A coastal sand bar of 1000–3000 m length prevents easy entry of seawater into the Bay that results in poor flushing and heavy siltation.

In general, the mangrove islets are seen as well-elevated with sharp vertical peripheral margin due to tidal wave action and erosion. The highly elevated lands lack regular tidal flushing and hence, the area is colonized with salt-marsh vegetation of *Suaeda* species. However, blank spaces are also seen at the middle area of mangrove islands, which are due to high salinity. Over-exploitation of fishery resources is a threat to mangroves. The seeds of tiger prawn are largely collected for aquaculture practices. Gastropods such as *Cerithidea cingulata* and *Telescopium telescopium* and bivalves such as *Anadara granosa* and *Meritrix* species are exploited for lime preparation. Golden jackal faces threat in its habitat due to destruction of mangroves in the Bandar Reserve Forest, Machilipatnam (Hindu, July 16, 2018).

Mangroves are excellent feed for cattle. It is believed that the livestock when fed with *Avicennia* leaves produces milk with high fat content. Buffaloes, goats, and cows are left among mangroves during the summer months and they graze *Avicennia* leaves and grasses (*Porteresia coarctata, Myriostachya wightiana, Aleuropus lagopoides*). Local people also collect the mangrove leaves in large quantities to feed their cattle. Other threats are due to salt manufacturing, replacement of mangroves by *Casuarina* plantation, sea level rise, and annual cyclones (Jayasundaramma et al. 1987; Prasad et al. 1997).

11.5.4 Tamil Nadu

Mangroves in Tamil Nadu are generally stunted and degrading in many places. The causes of degradation of mangroves are high salinity, low level of nutrients, and poor counts of beneficial microbes in the soil substrates. These are due to two reasons viz. (i) prevention of regular tidal flushing due to siltation at the river mouths and (ii) insufficient amount of freshwater and sediment from terrestrial sources to the estuarine mangrove areas. The entry of juvenile fishes from coastal sea to mangrove estuaries is reduced due to closure of the silted river mouth, while the movement of freshwater fishes to mangrove waters is reduced due to dam construction and poor flow of river water. These result in poor fish resources in the mangrove waters and poor fish catch (Kathiresan 2000a, 2002). Recently, the mangrove patches, particularly of *Rhizophora apiculata*, exhibit drying of trees in Pichavaram, the cause of which is not known.

Cattle grazing is another issue especially during monsoon. For example, in Pichavaram, the daily fodder requirement is about 7 tons for feeding 1800 cattle and goats, which utilize mostly the periphery of the mangrove forest for grazing, especially on *Avicennia* species. The propagules of *Avicennia* produced during monsoon are damaged by the cattle grazing, resulting in poor regeneration.

Mangrove wetlands emit the greenhouse gas such as methane due to heavy sewage discharges. For example, the emission of methane at the mouth of Adyar River in Chennai city is estimated to be much higher than other wetland areas (The Hindu, June 1, 2006).

11.5.5 Andaman and Nicobar Islands

In Andaman and Nicobar Islands, mangroves are less disturbed as compared to other mangroves along the peninsula of India. However, mangrove degradation does occur in very small pockets (Ramachandran et al. 1998). The factors responsible for degradation of mangroves are conversion for agriculture, encroachment, and tourism (Kumar 2000). The island systems are highly vulnerable to natural calamities. For instance, a sudden land drowning due to tectonic subsidence coupled with the 2004 tsunami caused heavy loss of mangroves in the Nicobar Islands.

11.5.6 Gujarat

In Gujarat, mangroves are affected by human interference for fodder, industrial development, and construction of salt pans, ports, jetties, and dams. Several mining, cement, and salt pan industries are developed along the mangrove forests, and this activity has resulted in increased siltation, salinity, and pollution in the coastal waters. In Kandla Port, a vast mangrove area has been reclaimed for port development. Construction of dams across rivers such as Rukmawati, Khari, Phot, and Bhukhi has changed flow patterns of water and increased salinity and siltation. Oil pollution is yet other threat to mangroves of Gujarat due to increased terminal pipeline passages and refineries (Thivakaran 1998). The oil spillage from pipelines near Narara Tapu and around Pirotan Island has caused mortality of mangroves.

Mangroves are the principal source of fodder for camel and cattle in the Gulf of Kutch and in the Great Rann. Due to large-scale felling of mangroves in the Gulf of Kutch, the siltation rate increased which caused depletion of the mangrove cover, especially in the Kori creek area of the Kutch. In the Gulf of Khambhat, the mangroves are heavily exploited for firewood.

Traditional livelihoods are threatened due to increasing industrialization. For example, the mangroves of Kutch are destroyed for developing the Mundra Special Economic Zone (SEZ), and this also cuts off land access to fishermen. The Mundra SEZ directly affects 1015 fishermen families by increasing cost of diesel, reducing fish catch, eviction, and displacement as well as lack of customary rights over the land they use as transient villages (The Hindu, July 2, 2008).

Many mangrove trees near Victor Port were cut down by a private company. Even a state enterprise indulged in mangrove destruction for the purpose of salt manufacturing. However, the forest department had planted nearly 140,000 mangroves between the years 2005 and 2017 to stop salinity ingress (Times of India, February 7, 2019).

11.5.7 Maharashtra and Goa

Mumbai coast had luxuriant mangrove vegetation till the year 1670, but since then, a large scale of reclamation and other developmental activities has destroyed the mangrove forests. Almost 70% of the mangroves were lost, leaving less than 45 sq. km in Mumbai. Slums proliferate all along the creeks of Mumbai and destroy the mangroves. Around 8000 illegal shacks have come up along the 10 km stretch in the past decade, adjoining Gorai creek. Similarly, about 2000 acres of mangroves were destroyed in Vasai creek and Thane creek during 2005–2010. The Ganpat Patil Nagar slum settlement along the Link Road in Dahisar is one of the largest slum pockets, after Dharavi, claiming more than 50 ha of mangroves (The Hindu, April 16, 2010).

In Mumbai's mangrove forests, pest attacks occur often during postmonsoon coinciding with changes in weather patterns, moisture availability, and intense rainfall. The pest attacks result in browning and drying of foliage. The attack is due to defoliating pests such as snails, caterpillars, and grasshoppers and their larvae that feed on leaves of mangroves especially *Avicennia marina.* Similar drying of mangroves has been observed in Hong Kong (1995), Rio de Janeiro, Brazil (2001), Ecuador (2008), and Indonesia (2019), and these countries either treated using pesticides or allowed natural regeneration of the pest attacked mangroves (Hindustan Times, September 17, 2020).

The Navi Mumbai international airport is a threat to mangroves for destroying 162 ha of mangroves, 404 ha of mudflats, and their biodiversity (Hindustan Times, August 31, 2018). According to the Bombay Natural History Society, the airport operations are likely to affect an estimated 266 bird species within 10 km radius of the airport site, including the Karnala Bird Sanctuary (The CSR Journal, February 7, 2019). Nearly 4500 mangrove trees were destroyed along the National High Road (NH-348) and approximately 3500 families residing in 10 villages were displaced (Times of India, December 27, 2018).

India's first high speed "bullet train" project is likely to result in the cutting of 53,467 mangrove trees in an area spreading across 13.36 ha in three districts of Thane, Navi Mumbai, and Palghar. The project has got wildlife clearance to the Mumbai-Ahmadabad bullet train corridor that encroaches upon a flamingo wildlife sanctuary and the Sanjay Gandhi National Park in Mumbai, for diversion of 1690 ha of bird heaven that includes 896 ha of mangroves and 794 ha of a water body on the western bank of the Thane Creek forest land.

The Bombay High Court on February 8, 2019 allowed the Maharashtra State Road Development Corporation (MSRDC) to cut 1585 mangrove trees on around 3 ha of mangrove forests for the Versova-Bandra sea link in Mumbai. The MSRDC has paid the cost of afforestation to plant a compensatory 11,000 mangrove tree planting by the Maharashtra Mangrove Cell. In Mapusa, Panaji, Goa, the mud dumped into the Tar River to facilitate dredging has damaged the mangrove-fringed channel.

11.5.8 Karnataka

Mangrove destruction continues with tree felling, agricultural operations, as well as soil dumping especially in Jokatte, near the Bykampady Industrial Estate, Mangalore (The Hindu, December 24, 2007).

11.5.9 Kerala

Kerala's entire coastal area was once covered with mangroves. This state had over 70 sq.km. of mangroves in 1975, but it reduced drastically to just 17 sq. km in 1991 due to removal of mangroves for agriculture, firewood, constructions of houses, and bunds (Ramachandran and Mohanan 1987). One major issue is that larger areas of mangroves are under private ownership. Yet another issue is coastal population density that has increased to as high as 2000 per sq. km. This high rate of population growth has resulted in acute land scarcity that led to widespread reclamation of mangrove wetlands. In addition, prawn farming, construction works, and uncontrolled discharge of wastes largely plastics, are also posing threats to the mangroves of Kerala, especially in Kannur district.

11.6 Conservation and Management of Mangroves in India

Despite increasing pressures, the mangrove forests are successfully managed in India by adopting three strategies: (i) promotory, (ii) regulatory, and (iii) participatory. In the promotory approach, the Government of India is implementing the Management Action Plan in 38 mangrove areas identified all along the coast (Table 11.13).

In the regulatory approach, India is strong on the policy front with adequate legal support for mangrove protection in the National Park, Wildlife Sanctuary, Reserved Forests, Protected Forests, and Community Reserves; however, effective implementation of the legislations is often constrained by lack of financial and human resources, poor infrastructure, and lack of political will. The mangroves are included as ecologically sensitive areas, and strictly protected under the Coastal Regulation Zone Notification 2018. Exemption is provided for defense and unavoidable public utilities with three times of compensatory plantations.

In the participatory management, stakeholders of mangrove conservation are involved, prominently in the states of Tamil Nadu, Odisha, Andhra Pradesh, West Bengal, and Gujarat (Kathiresan 2017). Joint Mangrove Management (JMM) has been demonstrated for restoration and conservation of mangroves through participation of local people along with forest departments by M.S. Swaminathan Research Foundation with financial support of Indo-Canada Environmental Facility (ICEF). The JMM project involved 5240 families from 28 villages along the east coast of

Table 11.13 Mangrove of India under management action plan

State/Union Territory	Mangrove sites
West Bengal	1. Sundarbans
Odisha	2. Bhitarkanika 3. Mahanadhi 4. Subernarekha 5. Devi 6. Dhamra 7. Mangrove Genetic Resources Center 8. Chilka
Andhra Pradesh	9. Coringa 10. East Godavari 11. Krishna
Tamil Nadu	12. Pichavaram 13. Muthupet 14. Ramnad 15. Pulicat 16. Kazhuveli
Andaman and Nicobar	17. North Andamans 18. Nicobar
Kerala	19. Vembanad 20. Kannur (Northern Kerala)
Karnataka	21. Kundapur 22. Dakshin Kannada/Honnavar 23. Karwar 24. Mangalore Forest Division
Goa	25. Goa
Maharashtra	26. Achra-Ratnagiri 27. Devgarh-Vijay Durg 28. Veldur 29. Kundalika-Revdanda 30. Mumbra-Diva 31. Vikroli 32. Shreevardhan 33. Vaitarna 34. Vasai-Manori 35. Malvan
Gujarat	36. Gulf of Kutch 37. Gulf of Khambhat 38. Dumas-Ubhrat

India and restored about 1475 ha of mangroves by planting 6.8 million mangrove saplings. A similar effort of community-based management of mangroves was undertaken by the Gujarat Ecology Commission with financial support of the ICEF. This project restored about 5000 ha of mangroves along the Gulf of Kutch and Gulf of Khambhat in 5 years from 2001 to 2006 (Kathiresan 2018a).

The Canal bank planting technique is practiced in rehabilitation of degrading mangroves in Tamil Nadu and Andhra Pradesh. In this technique, canals are formed with a "Fish Bone" design so that the high saline soil gets regular tidal inundation, leaches out salts, and becomes suitable for mangrove restoration. This effort was undertaken with participation of local people that resulted in increased forest cover by 90% in the degraded mangrove areas of Pichavaram, between 1986 and 2002 as proved by satellite data (Selvam et al. 2003).

Maharashtra State has successfully demonstrated mangrove conservation. The Bombay High Court order on October 6, 2005 prohibited all constructions in the mangrove areas and within 50 m radius from the mangrove boundary. The order directed to declare the mangroves on government land as "protected areas" under the Indian Forest Act and also to transfer the mangroves to the forest department. As a result, 5469 ha of mangroves on government land were transferred to the Thane Forest Division by the revenue authorities. Further, the status of mangrove forests on government land was elevated from "protected forests" to "reserved forests" by the Government of Maharashtra. This led to notification of 15,088 ha of mangroves on government land as "reserved forests" in seven districts of Maharashtra. The Maharashtra Government has a total mangrove forest land area of 30,200 ha that include 14,888 ha under private land, and the government has so far notified 15,312 ha of the land as reserved forest under the Indian Forest Act. Of 15,312 ha however, 1592.8 ha are yet to be transferred from the revenue department to the forest department for better protection as per the Bombay High Court directive on September 2018 (The Hindustan Times, September 19, 2020).

The Government constituted a "Mangrove Cell" in January 2012, which achieved plantation in more than 200 ha of mangrove degraded areas in the Greater Mumbai region. In addition, the cell helped in the notification of the "Thane Flamingo Sanctuary", which spreads over an area of 1690 ha that supports 10 mangrove flora species and 200 bird species. The cell also promoted crab, oyster, and seabass fish farming practices in the mangrove waters, as a supplementary livelihood for the benefit of the local people in Sindhudurg district. Furthermore, the cell demonstrated a cross-sectoral approach toward marine and coastal conservation, in partnership with leading national institutions, agencies, NGOs, and with a wide range of Government Departments such as Fisheries, Agriculture, Tourism, Police, Revenue, and Urban Development (Vasudevan 2017).

Maharashtra Government is the first state to declare *Sonneratia alba* as the state official mangrove tree. The "Mangrove Cell" in 2012 received funds from developmental projects for wildlife approval for implementation (2% of total project cost). Interest derived from a fixed deposit of the money is spent for activities for the cell, thereby they are not dependent on government funds. This is a model for successful mangrove conservation programs.

Another successful effort of mangrove conservation is in the district of Kannur, Kerala. The district administration started a program called "Mission Mangrove Kannur" and undertook a comprehensive survey of mangroves with the help of revenue and forest departments for 14 months during 2014–2015. As a result, 236 ha of mangroves were notified as "Reserved Forest" for conservation. In addition, the district administration also initiated the process of acquisition of 1200 acres of mangroves from private owners (Bala Kiran 2017).

Chinese environmentalists want to learn from the Indian experience in protecting mangroves. This is due to the heavy task of saving their country's mangrove wetlands from increasing developmental pressures such as, tourism and rapid expansion of shrimp aquaculture with diminishing bird populations and reduced natural resources, particularly in the mangrove areas of the Hainan province and the Zhanjiang National Nature Reserve in Guangdong (The Hindu, April 14, 2012).

There was a devastating Cyclone Amphan in May 2020 in West Bengal. The Government of West Bengal immediately drafted a mangrove recovery plan of planting 50 million mangrove trees in the Sundarbans to compensate the loss during the cyclone. However, there is a lack of adequate space for planting the mangroves. An area of 10,000 ha is required to plant mangroves at the rate of 5000 per ha. But most of the space available is only in the interior islands, which are unsuitable for planting due to arid and saline conditions. Only limited areas are available for mangrove planting. The Indian Sundarbans are spread over 9630 sq. km; of which, 5400 sq. km are inhabited by humans, while the rest 4260 sq. km is forests with 50% water area. It is necessary to allow a period for natural recovery of the ecosystem as the mangroves are efficient in new growth of shoots after cyclone damage due to the presence of an apical meristem especially in non-*Rhizophora* mangroves species.

11.7 Concluding Remarks

India had a mangrove cover of 6000 sq. km during the 1960s, and it reduced to 4975 sq. km in 2019. However, since 1995, the mangrove cover has stabilized close to 4500 sq. km with an increasing trend, despite increasing pressures. It will be possible to achieve the target of 6000 sq. km of mangrove cover within a period of 10 years, if the restoration is increased at the annual rate of 100 sq. km. In this regard, the best proven practices of participatory management can be suitably replicated in all mangrove areas of the country. The mangrove forest in India has increased by 54 km^2 in the 2 years from 2017 to 2019. This has resulted in enhanced fish stock and carbon storage; economic value of which is estimated to be many fold greater than the cost of restoration, and hence it is a cost-effective venture, deserving much focus on rehabilitation of degrading areas especially in unprotected areas (Kathiresan 2021a).

Even though the Sundarbans occupies 43% of total Indian mangrove cover, its increase has been only marginal in the past two decades but reduced by 0.09% in the recent past (2017-2019). This deserves much attention in providing more effective governance and better ways to rehabilitate degraded mangroves and to create new mangrove habitations through intensified afforestation programs. A large area of mangrove forests fall under the Tiger Reserve where human activities are prohibited. Its future depends on the local people's action that will protect the river banks from erosion, and the policies that address the pressure imposed on natural resources.

Mangroves have organic-rich soil exceptionally high in carbon storage. When the mangroves are disturbed, the carbon losses are high and result in greenhouse gas (GHG) emissions. Among the GHG emissions, CH_4 and N_2O account for only a small fraction of total GHG emission from the deforestation, but they are more effective at trapping heat up to 300 times in the atmosphere when compared to CO_2. These emissions can be avoided by reducing land conversion or by increasing restoration efforts. Deforestation for aqua-farm constructions can increase GHG emissions by more than 10 times from mangrove forests. Mangrove restoration can be a novel counter-measure for global warming as it reduces atmospheric CO_2 (e.g., Kathiresan et al. 2013a; b; Kathiresan et al. 2014; Kathiresan et al. 2021). This deserves the attention of policy makers in planning for utilization of mangroves in the carbon market and trading as well as REDD (Reducing Emissions from Deforestation and Forest Degradation). It is important in the present context that India has a target to create an additional carbon sink of 3 billion tons of CO_2 equivalent through additional cover of all the forests by 2030. In this regard, mangrove forests will be a promising option as a blue carbon sink.

A large tract of mangrove cover (that is 40.6% of total) is open-type forest with less dense vegetation. For instance, Gujarat occupies the second largest part of mangrove cover in India, but 85.6% of which is open type and degrading (SFR 2019). The open type of mangroves may be more vulnerable to natural and anthropogenic stressors. In addition, the Indian mangroves are degraded five-fold more in unprotected areas than that in protected areas (Worthington and Spalding 2018). Hence, rehabilitation of degraded mangrove areas deserves much attention especially in unprotected areas for restoration of ecosystem services. Moreover, it is necessary to take efforts in transforming the open type in to dense forest.

Mangrove planting efforts are often a failure in several instances. There was 46% failure in 48 restoration sites with 127,832 ha of area restored in south Asian countries being the highest failure of the restored sites in other regions of the world (Worthington and Spalding 2018). Furthermore, planting is commonly practiced with only a few species of fast-growing mangroves such as *Rhizophora* and *Avicennia*, and this has reduced biodiversity and ecosystem functions of the restored mangroves. In this regard, “ecological restoration” is essential to provide the right tidal water flow and land elevation for natural regeneration, and also planting with suitable species for accelerating recovery. A continuous monitoring of growth and survival of mangrove species is necessary in addition to maintaining the normal tidal water flow, supplementary planting, weed/pest removal, trash removal, cattle grazing prevention, and desiltation in the restored areas, besides assessing the ecological and economic benefits (Lewis and Ben 2014; Kathiresan 2018a). Efforts are largely required on protection of mature forests, hydrological restoration, and restoration of damaged habitats such as abandoned shrimp ponds. Large-scale plantation must be the last option.

Mangrove loss is caused by human activity and natural stressors. Although human activity is a dominant cause, its impact on mangrove loss has declined since 2000 due to conservation efforts. However, natural stressors such as extreme weather, coastal erosion, and sea level rise are increasingly affecting the mangroves, and hence the natural stressors are of immediate challenge which deserves attention.

Mangroves possess bioprospecting potential as a source of valuable chemicals, genes, and products of commercial value. The mangroves are reported for high value products such as (i) black tea beverage, (ii) mosquito repellents, (iii) lignins for controlling oral and cervical cancers, (iv) polysaccharides for preventing the Human Immunodeficiency Virus (HIV) that causes AIDS, (v) antidiabetic extract, (vi) hair growth stimulant, and (vii) rapid synthesis of nanoparticles, as proved in our laboratory (Kathiresan and Ravikumar 2010; Kathiresan 2020). Further studies in this aspect will lead to the development of patents, processes, and valuable medicinal products. This will help in revenue generation and employment opportunities.

Saving the mangroves without strengthening the livelihood of local communities living in the vicinity will never be successful. Participatory management in conservation and wise-use of the precious mangrove resources will ensure the ecological security and economic prosperity of coastal India.

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Chapter 12
Mangroves of Sundarban

Sudhir Chandra Das

Abstract The Sundarbans are the largest delta of mangroves in the world comprising 10,277 km^2 at the meeting of two Himalayan rivers, the Ganges and Brahmaputra. The Sundarbans span India's state of West Bengal (4260 km^2) to Bangladesh (6017 km^2). The Sundarban mangroves are important in respect of species diversity, richness in mangrove flora and fauna, mangrove abundance and unique succession features. The Sundarbans provide 'home' for globally threatened species like Royal Bengal tiger, fishing cat, Gangetic dolphin, estuarine crocodile, horse shoe crabs, water monitor lizard and river terrapins. Mangrove forests provide a large amount of fish catch (up to 80%), thereby supporting the livelihood and ensuring the food security of coastal people. The mangroves of Sundarbans are endangered and are in an alarming state due to present trends of over- exploitation and large-scale dependency of an enormous rural population of the Lower Gangetic Delta. Sundarbans mangrove ecosystems, ecological and socio-economic services have also not been considered in the past and the mangroves have been developed for prawn and fish farms. However, these problems are now being addressed through the Joint Forest Management (JFM) system for better management of mangroves in Sundarbans.

Keywords Mangroves · Delta · Dependence · Species diversity · JFM · Exploitation

12.1 Introduction

Sundarbans, the largest delta of the world, is the much talked about natural resources site and it is a privilege for India and Bangladesh to have such a wonderful place of natural wildlife habitat. It spans from the Hoogli River in India's state of West Bengal in the western side to the Baleswar River of Bangladesh in the eastern site. Sundarban Mangrove is a unique ecosystem. This delta is formed in the inter-tidal areas at the confluence of two mighty Himalayan rivers, viz. the Ganges and the Brahmaputra with Bay of Bengal. Area of Sundarban region is 10,277 km^2 of which

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6017 km^2 in Bangladesh and 4260 km^2 in India. It is criss-crossed by riverine streams, canals and creeks and lies just south of the Tropic of Cancer between latitudes 21°32′N and 22°40′N and longitude 88°10′E and 89°51′E. It is considered as a self-maintaining coastal, inter-tidal estuarine component, which thrives due to constant interaction with the terrestrial and marine ecosystem. The pristine deltas of the Sundarbans are located at the southernmost fringe of Bangladesh and West Bengal, a state of eastern India. Since time immemorial, Sundarbans are considered to be a topic of immense ecological significance by scholars and researchers. This was brought under 'Project Tiger' in 1973. The immense biodiversity and ongoing geological processes led to further accolades as the reserve was declared a World Heritage Site by UNESCO in 1987 for Indian part and in 1997 for Bangladesh part. The Sundarbans are the treasure-trove for naturalists and scientists, a paradise for nature and wildlife photographers and a wonderland for tourists from all over the world.

Sundarbans is one of the largest deltaic zones which has attracted the interest of world-renowned botanists and ecologists since the later part of the eighteenth century. On the basis of his own work and the collections of others, William Roxburgh documented the first authentic work on this Lower Ganga Delta which was published in Roxburgh 1814 under the title 'Hortus Bengalensis'. The pioneer workers on Sundarbans were Voigt (1845), Anderson (1862), Schlichs (1875) and Clarke (1895). Based on these collections, Prain (1903a), Prain 1903b and Prain 1905 also published the monumental works on the 'Flora of Bengal' in general and the Flora of Sundarbans in particular. Over the course of time, the overall landscape of the Bengal basin in general and Sundarbans in particular has changed due to geological and geographical changes and the rapid growing human interaction and population pressure on these Sundarbans (Naskar and Guha Bakshi 1987). The current assessment by the Forest Survey of India (2019) through analysis of satellite imagery shows very dense mangrove comprises 29.66% of the mangrove cover, moderately dense mangrove is 29.73% while open mangroves constitute 40.61% of mangrove cover. Sundarbans also provides shelter to a wide variety of faunal species both terrestrial and aquatic. It provides excellent habitat to the Royal Bengal Tiger, estuarine crocodile and their prey-base.

12.2 Physical Attributes

12.2.1 Geology, Rock and Soil

The Sundarbans delta is the largest prograding delta of the globe. The formations of different lithologic units of deltaic deposition in this system took place at major shifts of strand lines. The high strand shoreline was far west 215,000 years back, a strandline change took place 82,000 years back and the present deposition of detritus formed since the last 6000 years of stable phase. There is general slope towards south as well as west to east. The upper 100 m layer is composed of thick clay with occasional clay balls. There occurs unconsolidated sediment at 137 to 152 m depth composed of sand, silt and clay and gravels of varying colours. This serves as a boundary for the upper aquifer. At about 350 m depth, there lies a second aquifer of potable water. The whole sediment is composed mainly of montmorillonite, which is very sticky. They are derived from the basic and semi-acidic rocks like Dolerite, Gneiss and Mica schists lying within the course of Ganga flow. Soil salinity reaches up to 3%. The older the sediments the higher the salinity in the Sundarbans area.

The Sundarbans saline soils are considered to cause higher plant mortality and the white salt encrustations are very often visible on the soil surface. The salinity rises to the maximum in the middle of May and decreases on the onset of monsoon. The salt contents are mostly chlorides and sulphates of sodium, magnesium and calcium, though bicarbonates are also present in traces. The subsoil layer remains under reduced condition along with mottles of different sized dark coloured horizons. The soil pH ranges between 5.4 and 8.5 in reaction. In submerged condition and with higher salinity, the decomposition rate of the organic matter is less as the bacterial population in those areas is generally poor (Qureshi 1957). The organic matter decomposition in these tidal zones is carried out by some facultative and obligate anaerobic bacteria. Mangroves usually have a low decomposition rate of root biomass relative to root production, which results in the accumulation of organic matter in the soil.

12.2.2 Hydrology and Water Sources

12.2.2.1 River Systems

A close network of rivers, channels and creeks intersects the whole area, which has resulted in formation of innumerable flat islands. These are submerged completely during high spring tides and partially during ordinary high tides. The main rivers in the Indian part of the Sundarbans are Hoogli, Thakuran, Matla, Bidyadhari, Goasaba, Jhilla, Harinbhanga, Kalindi and Raimangal. In Bangladesh, the Ganges delta is formed by the confluence of the Ganges (locally called Podda), Brahmaputra (locally called Jamuna) and Meghna rivers and their tributaries (Fig. 12.1). The Ganges unites with the Jamuna and later joins the Meghna, finally flowing into the Bay of Bengal. Bangladesh has 57 trans-boundary rivers. The existing large rivers running north to south are the remnants of the old courses of the Ganga. During the sixteenth to eighteenth century, the Bengal basin was affected by a neo-tectonic movement by way of which an easterly tilt came along a hinge zone, i.e. from Sagar to north of the district of Malda, West Bengal, and then gradually curving towards Dhaka, Bangladesh. As a result of the trend of surface elevation contours ENE-WSW, the present course of Ganges, which used to flow along the course of Tamralipta till twelfth century A.D., started flowing along the river Padma within Bangladesh leaving Hooghly as a mere tidal channel. Even till the early eighties, the

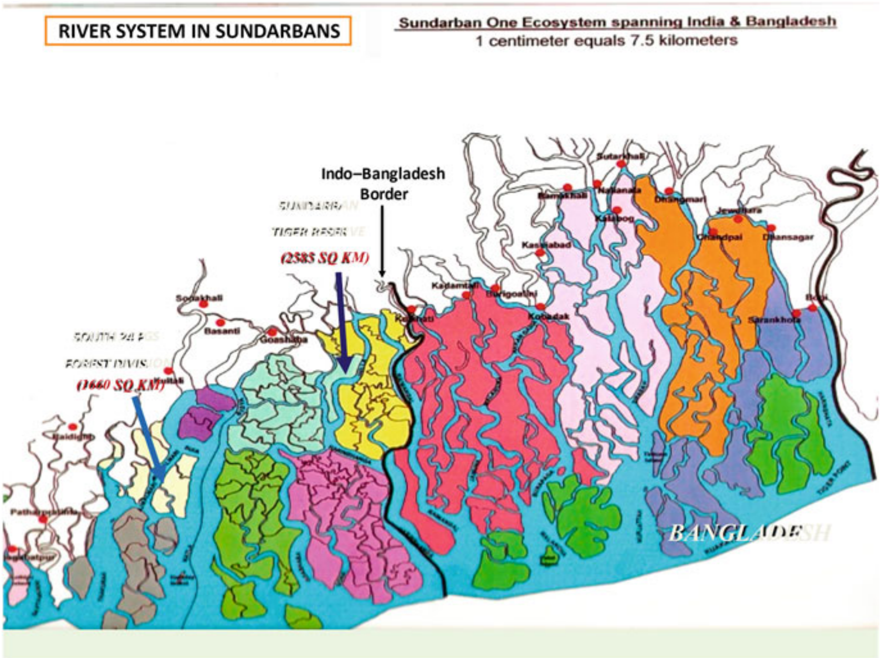

Fig. 12.1 River system in Sundarbans (both India and Bangladesh)

tidal effect of Hooghly could be felt up to 281 km upstream up to Nabadwip in the district of Nadia, West Bengal. During this period, the Matla and Bidyadhari river system formed an innumerable network of creeks between Ganges and Padma; however, these river systems got completely cut off from sweet-water source and are presently fed by the backwaters of sea.

During the rains, the Raimangal receives an overflow of the Ganga through the Ichhamati, which connects them. The rivers Matla, Saptamukhi and Thakuran lying on the Western side have practically no connection with their original parent stream and are now creeks of the sea. These are highly brackish all the year round in comparison with the Hooghly and the Raimangal. The Hooghly is fed mainly by the Rupnarayan and is also connected with the Ganga through the Jalangi and the Bhagirathi. However, the estuary of the Hooghly remains brackish even during the rains on account of its great width. With the coming up of Farakka Barrage, sweet-water flow in Hooghly has increased and is now brackish below Diamond Harbour. The sources of all the rivers in the western Sundarbans are being progressively silted up leaving hardly any passage for freshwater, with the result that the rivers are getting more brackish and shallow year after year.

12.2.2.2 Climate

The climate is tropical, moist, warm and equable. The humidity is uniformly high and temperature is equable due to its proximity to the sea. It receives good amounts of rainfall and is humid for most parts of the year. The temperature varies little throughout the year, mean annual temperature is close to 27 °C, maximum is 32 °C and minimum is 22 °C. The mean annual rainfall of the Sundarbans is 1920 mm. The west coast and Andaman get a high rainfall of over 3000 mm. The atmospheric humidity is 73% to 80% and is more or less uniform throughout the year. During the months of January and February, dense ground mists occur in the early morning. The summer extends from the middle of March to the middle of June and the winter extends from December to February. The climate is more equable in the areas covered by forest than in the neighbouring cleared areas. The monsoon starts usually between the middle of June and lasts up to the middle of September. Overall, the rough weather lasts from 15th March to 15th September and the fair weather prevails between middle of September to middle of March.

The prevailing wind is from north to north-east from the beginning of October to middle of March. January to February is calm. The wind commences to blow violently from south-west from middle of March to end of September. Storms are common; some of these often develop into cyclones of varying intensity accompanied by tidal waves and cause much damage to forests. The vast block of forest acts as a barrier and reduces the severity of the gales. Apart from damage to standing trees, there is intensification of flow tides and retardation of ebb tides caused by such winds. Every year, 4–5 cyclonic storms are common. These are of common occurrence in the lower Ganga delta during mid-March to mid-June and occasionally during October to November. During cyclones and storms, the sea or the river water rises up much more than what it normally rises. The accompanying winds impart it with much force with which the waves dash against the surrounding areas. The funnel shape of the Bay of Bengal in the lower part of the Gangetic delta, poses the most serious threat, from the surges, driven by storm waves (Fosberg and Chapman 1971).

12.2.2.3 Tidal Amplitude

In the Sundarbans, high-tides and ebb-tides occur twice daily and the current changes its direction every 6 h. The spring tides, which occur at the vernal equinox (March–April), produce the maximum rise and fall, as there is very little current in the rivers during this time. The tidal current passes from west to east, so the change of tide is earlier in the west than in the east. The velocity of the tidal current increases in the northern part of the tract where the rivers are narrow and the maximum rise and fall occur where the speed is the highest. Near the sea coast, the average rise and fall is about 2.15 m. While a south wind prolongs the period of the flow, a north wind shortens the same. The maximum and minimum tides recorded at Sagar Island (west part of Sundarbans) are 5.68 m and 0.96 m, respectively.

However, as a rule, the flood tide in the estuarine system lasts more than the ebb-tides. The resulting effect, unless there is excess river energy from upstream flush, the decantation of traction load sediments takes place. Thus, these backwater channels are getting silted up day by day. With the change in seasons, tidal interactions in the estuarine system in and around the Indian Sundarbans also change (Pillay 1954). During the monsoon months, the effect of flood tide is more or less countered and nullified by freshets and there is a strong predominance of ebb-tide. The strength of flood tide over ebb-tide is at a minimum during the post-monsoon season. Conversely, during the pre-monsoon season, the effect of flood tide is considerably stronger than that of the ebb-tide.

12.2.2.4 Water Supply

Cultivation in Sundarbans is solely dependent on rainwater. The fishermen, honey collectors and woodcutters carry large earthen pots for carrying their ration of sweet waters whenever they go to the field. There is acute scarcity of sweet water in the islands. A deep tube-well (nearly 300 m deep) has been sunk at Bidya station and is the primary source of water for all touring launches and few camps where there is no source of drinking water. To date, deep tube-well boring has been unsuccessful in most of the islands. Most of these field camps have freshwater ponds and recently, rainwater harvesting has been carried out, where rain water is collected and stored in large aboveground and underground tanks. This has given encouraging results and shall be replicated in other camps as well. Tanks are generally dug down to the layer of impervious sodic clay. Rainwater stored therein is subsequently bailed out. By such repeated washing with rain water in about 3 years, a tank becomes sweet.

12.3 Floral Biodiversity

The mangrove forest of Sundarbans is a very dynamic ecosystem. It is in a continuous state of erosion and accretion leading to subsidence or erosion of existing banks and appearance of new lands and mud flats. Flora is very rich in the Sundarban forests in comparison to other mangrove areas in the world. There are 61 species of true mangrove and 69 species of mangrove associates (Fig. 12.2).

12.3.1 Vegetation Type

Mangroves and mangrove associates constitute the dominant vegetation type of the area. Champion and Seth (1968) made one of the most comprehensive assessments

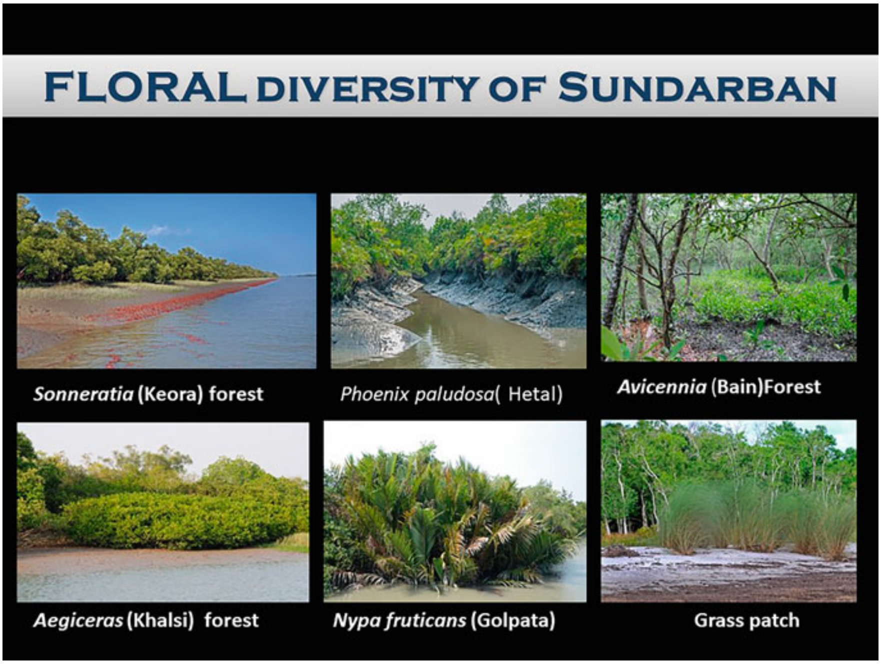

Fig. 12.2 Glimpses of floral diversity in Sundarbans

of the vegetation communities of the Indian Sundarbans. They divided the forest into categories based on broad characteristics of physiognomy and structure. These communities were defined irrespective of physiographic, edaphic or biotic factors. They were of the opinion that some communities were clearly associated with a definite site factor, which differed appreciably from the surrounding areas. According to Champion and Seth's (1968), Tidal Swamp forests are classified under sub-group 4B with following sub-divisions.

12.3.1.1 Mangrove Scrub: Sub-Type 4B/TS$_1$

It is known as low mangrove forest or salt-water forest occurs on soft tidal mud submerged by salt water by every tide. It is a dense forest of low average height of 3–6 m. In the upper canopy, the promising species are *Ceriops decandra, Avicennia alba, Aegialitis rotundifolia, Excoecaria agalllocha, Phoenix paludosa* (drier ground). *Acanthus ilicifolius* often forms the undergrowth. Local patches of grass may also be seen. Few species are markedly gregarious, all evergreen with leathery leaves. Vivipary is seen, common in Western Sundarban.

12.3.1.2 Mangrove Forest: Sub-Type 4B/TS_2

It is known as tree mangrove forest. It is typically an evergreen forest of moderate height composed of trees specially adapted to survive on tidal mud which is permanently submerged with salt water and is submerged by every tide. It is found on mud banks of delta streams and near sea-face where accretion is in progress. Stilt roots are very typical in *Rhizophora,* leaves are leathery and vivipary is seen. The upper and lower storeys are composed of *Rhizophora mucronata, Kandelia candel, Avicennia alba, Excoecaria agallocha, Ceriops decandra, C. tagal, Bruguiera gymnorhiza, Xylocarpus granatum, Sonneratia apetala* in West Sundarbans. In Krishna, Godavari and Mahanadi deltas, *Avicennia officinalis* is the principal species, the associates consist of *Rhizophora mucronata, Ceriops decandra, Sonneratia apetala, Bruguiera gymnorhiza* and *Acanthus ilicifolius*.

12.3.1.3 Salt-Water Mixed Forest (*Heritiera*): Sub-Type 4B/TS_3

It is known as moderately salt-water forest, occurs behind and above the previous two types. This type of forest occurs where ground is flooded by every type with definitely brackish water. The forest is fairly dense with trees up to 20 m height and the trees never attain large girth. Pneumatophores are typical. There is less silt deposition and the soil has less humus. The upper and lower storeys are composed of *Heritiera fomes*, *Excoecaria agallocha*, *Ceriops decandra*, *Xylocarpus mekongenesis*, *Avicennia officinalis*, *Aegialitis rotundifolia* (near sea-face). A light ground cover of *Nipa fruticans* is sometimes found.

12.3.1.4 Brackish-Water Mixed Forest (*Heritiera*): Sub-Type 4B/TS_4

It is known as freshwater forest occurs primarily in the deltaic region of the Ganges. This type represents the finest and the most valuable form of the tidal forest and it is poorly represented in the western part of Sundarbans. The major portion of this type represents in the eastern part, i.e. in Bangladesh. Height of the trees may reach up to 33 m. The ground is flooded for some portion of each day by water which is either quite fresh or slightly brackish. There is good deposit of silt every year. The upper canopy is composed of *Heritiera fomes*, *Sonneratia apetala*, *Xylocarpus mekongenesis*, *Bruguiera* sp., *Sonneratia caseolaris*, *Excoecaria agallocha*, *Ceriops decandra*, *Phoenix paludosa* (high land), *Acanthus ilicifolius*, *Nypa fruticans* (fringing banks).

12.3.1.5 Palm Swamp Type: Sub-Type 4B/E_1

It is mainly represented by *Phoenix paludosa.* It is seen on drier areas within salt-water mangrove scrub or mangrove forest. Forest area is partly flooded for some part of the day.

12.3.2 Vegetation Succession

Naskar and Guha Bakshi (1987) worked extensively on the succession of mangrove flora. They identified five ecological successions of the Sundarbans swamp based mainly on tidal magnitude, viz.

- Phase I: Swampy Mangrove or Intertidal Mangrove Zones.
- Phase II: Tidal Mangrove.
- Phase III: True Mangrove Decline.
- Phase IV: Colonisation of non-littoral species.
- Phase V: Xerophytic non-mangrove and dry evergreen forest.

The mangrove forest is a very dynamic ecosystem. It is in continuous state of erosion and accretion leading to subsidence or erosion of existing banks and appearance of new lands and mud flats. Mangrove succession starts with the appearance of the pioneer species locally known as dhani ghas (*Porteresia coarctata*) (Fig. 12.3) on the newly arisen mud flats. With the passage of time, this grass species traps the propagules of *Avicennia* and *Sonneratia* sp., which come up well in freshly silted and firm mudflats. Once the land gets consolidated, *Ceriops* sp. and *Excoecaria agallocha* come and colonise the area. *Phoenix paludosa*

Fig. 12.3 Mangrove succession starts with *Porteresia coarctata* followed by *Avicennia* sp.

considered as the climax species which comes upon high lands and forms gregarious growth.

In general, the northern boundary and new depositions are characterised by Bain (*Avicennia marina, A. alba, A. officinalis*) flanked by foreshore grassland of *Porteresia coarctata.* Bain is gradually replaced by Gnewa (*Excoecaria agallocha*) and then Goran (*Ceriops decandra*). About 70% of the area is covered with Gnewa-Goran association. There are, however, southern and eastern associations of Garjan (*Rhizophora apiculata*, *R. mucronata*), Kankra (*Bruguiera sexangula*, *B. gymnorhiza*, *B. cylindrica* and *B. parviflora*) and patches of Sundari (*Heritiera fomes*)–Gnewa–Goran. Pure Hental (*Phoenix paludosa*) forests exist on relatively high lands. These Hental forests are considered as the climax vegetation. *Xylocarpus granatum* and *X. mekongensis* are distributed throughout the forests. *Nypa fruticans* palm swamp is common on central, eastern and southern portions, alongside creeks and rivers having soft mud deposition. The sea-facing areas have *Excoecaria* sp., *Lumnitzera racemosa*, *Saccharum*, *Derris indica*, *Thespesia populnea*, *Ipomea pes-caprae*, etc.

Heritiera fomes, which was once found throughout the area, has over the years become confined to the eastern and southern sector. This shift in distribution has been attributed to the gradual reduction of sweet water into the system as the river sources have been cut off from their origin owing to siltation and are purely arms of the sea, thereby leading to an overall increase in the salinity regime.

12.3.3 Mangrove Species Preferred by Wildlife

The species most favoured by the herbivores is Keora (*Sonneretia* spp.) whose fruits and leaves are preferred by Spotted Deer (*Axis axis*) and *Rhesus macaque*. Pangas fish (*Pangasius pangasius*) has been found to eat Keora (*Sonneretia* spp.) fruits. Apart from this, fresh shoots of Hental (*Phoenix paludosa*) are browsed by Spotted Deer (*Axis axis*) and *Phoenix* fruits are preferred by birds and macaques. *Avicennia* and *Excoecaria* are also browsed quite often by the herbivores. Succulent tips of dhani grass (*Porteresia coarctata*) growing on newly colonised mud flats have also been seen to attract Spotted Deer (*Axis axis*) herds. The flowers of *Bruguera gymnorhiza,* when shed and float in water are a good source of food for river Terrapin (*Batagur baska).*

12.4 Faunal Biodiversity

12.4.1 Historical Perspective

A detailed account of the wildlife, which was once present in the area, is given in the Hunter's Statistical Account of Sundarbans (Hunter 1878). Some excerpts of which are reproduced below:

'Tigers, leopards, rhinoceros, wild buffaloes, wild hogs, wild cats, barasinga or large deer, spotted deer, hog deer, barking deer, porcupines, otters and monkeys are the principal varieties of wild animals found in the Sundarbans. Tigers are very numerous, and their ravages form one of the obstacles to the extension of cultivation.

The serpents found in the Sundarbans are the boa constrictor, cobra-di-capello or gokhura, kuriat, sankhachur or salt-water snake, gosap and green viper.

The birds of Sundarbans comprise the following: Adjutants of two kinds, viz. *Ardea gigantia* and the Marabout adjutant–vultures, kites, hawks, owls, mynas, doves, green pigeons, parrots, parroquets, jungle-fowl, woodpeckers, sandpipers, egrets, waders, large and small spoonbills, pelicans, storks, paddy birds of several kinds, herons, snipe, crows, several varieties of kingfishers, divers, hornbills, jays, orioles, teal, seagulls, curlew, Indian pheasants, waterfowl, reedbirds, plovers, partridges and a great variety of wild geese and ducks.

The fishes abound in nearly all the rivers. Porpoises and crocodiles (commonly called alligators) abound but the latter are less numerous than they were 20 years ago.

The Sharks also are by no means uncommon in the larger streams and estuaries. No trade is carried on in wild beast skins, with the exception of the skins and horns of the spotted deer, which are sold for a trifle and to a very small extent'**.**

However, over a period of time we have lost a number of animals due to ecological changes, habitat degradation and related anthropogenic activities. Some of the animals, which were once present but have been lost, include Javan Rhinoceros, Wild Buffalo, Swamp Deer, Barking Deer and Hog Deer.

A total of 1434 faunal species have been reported so far from Sundarbans (Nandi et al. 1993) from terrestrial, intertidal and aquatic environments. These animals comprise 989 species of invertebrates, one species of hemichordate and 445 species of vertebrates. It is also reported that 486 species from supralittoral zone, 499 species from tidal flats and 449 species from estuarine waters. Phylum-wise major contributors are

1. 476 species of Arthropoda of which 240 species are Crustacea, 201 species of Insecta and 33 species of Arachnida.
2. 445 species of Chordata of which 154 species are Osteichthyes, 22 species of Chondrichthyes, eight species of Amphibia, 58 species of Reptilia, 163 species of Aves (110 resident and 53 migratory) and 40 species of Mammalia (five species of Dolphin and Porpoises are aquatic and rests are terrestrial).
3. 142 species belong to Phylum Mollusca.

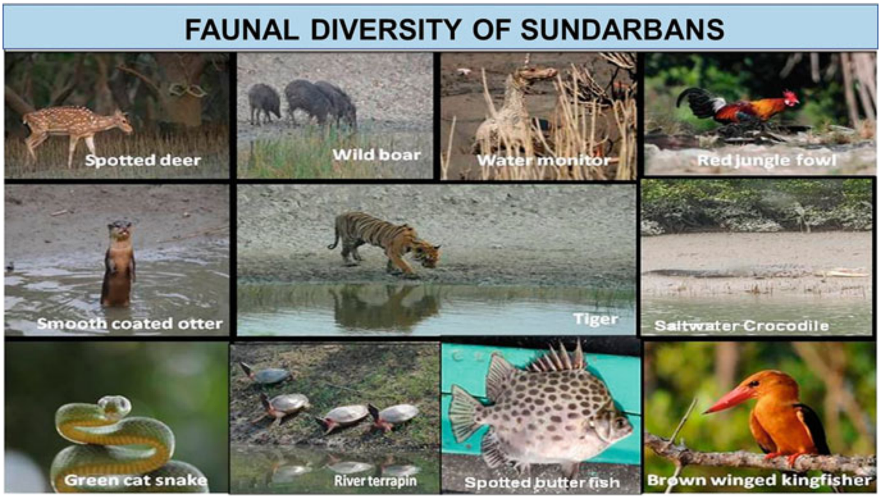

Fig. 12.4 Glimpses of fauna diversity in Sundarbans

The terrestrial mangrove ecosystem in Sundarbans is the domain of the Royal Bengal Tiger, *Panthera tigris tigris,* which is at the apex of the food chain. It is the only mangrove-tiger kingdom in the world and presently harbours 95 tigers in Indian Territory and 105 tigers in Bangladesh. The estuarine crocodile (*Crocodylus porosus*) is the top-most predator in the aquatic ecosystem. Apart from the estuarine crocodile, the water monitor lizard (*Varanus salvator*) which reaching up to 2.4 m in length can be frequently found within the reserve. About 11 species of crabs found within the creek waters. The Gangetic shark (*Glyphus gangeticus*) is also found in Sundarbans. Current observations of fauna in the Sundarbans (Fig. 12.4).

12.4.2 The Current Status

Mangrove fauna is found to occur in both the terrestrial and the aquatic ecosystems. These areas can be differentiated as:

The littoral or supra-littoral (i.e. areas beyond the high tide) forest biome is typically a terrestrial environment, which includes both aerial and arboreal forms and the soil inhabitants. The inter-tidal (region between high- and low-tide) mudflats are essentially semi-terrestrial or semi-aquatic habitat supporting mainly the soil forms and the benthos. While the other faunal components in the mudflat and estuary can broadly be divided into zoo-plankton, nekton and benthos. Several species of crustaceans and larvae of fishes form the main component of the zoo-plankton in this region. The pattern of distribution of animals in mangrove ecosystem is influenced by the substratum, salinity, tidal amplitude, vegetation, light and temperature.

12.4.2.1 The Arboreal Community

Animals under this community include both aerial and arboreal forms. The upper canopy of mangrove trees is the home of birds, bats, monkeys and insects. For example, the Pigmy pipistrella, *Pipistrellus mimes* can be found flying on the onset of evening inside the Tiger Reserve areas. The Rhesus macaque (*Macaca mulatta*), the only species of primate occurring in the Sundarban is well-distributed in the entire forest. They are often found feeding on Keora trees (*Sonneratia apetala*) but are also well adapted to crab eating. It is interesting to note that herds of deer follow the troops or Rhesus Monkey from one Keora tree to another in search of leaves that the monkeys drop from the trees tops in course of their feeding; the deer also get advance information about the movement of the tiger from the monkey's call.

Many species of birds build their nests in the mangrove trees. Herons, Egrets, Cormorants and Darters enjoy roosting in colonies on the tall trees of Bain, Sundari and Genwa. The *Sonneratia* tree is especially preferred by parakeets and woodpeckers, several species of birds use trunk, branches and aerial roots of mangrove as observation posts for feeding.

Honey bee, i.e. *Apis dorsata* is responsible for pollination in about 80% of the mangrove species, thereby plays a very important ecological role in the mangrove forests. These bees are known to build their honeycomb inside the forest in large numbers. Yearly more than 20 tonnes of honey is produced by the bees in the entire Sundarbans area. About 39% of honey is produced from *Excoecaria agallocha* (Genwa), 16% from *Avicennia* species (Bain), 11% from *Ceriops* species (Goran), 10% from *Rhizophora* species (Garjan) and only 24% from the rest of the plants. *Phoenix-Excoearia* (Hental-Genwa) association is thought to be the ideal sites for honey comb formation.

12.4.2.2 Terrestrial and Aquatic Community

12.4.2.2.1 Mammals

The terrestrial mangrove ecosystem in Sundarbans is the domain of the Royal Bengal Tiger, *Panthera tigris tigris,* (Fig. 12.5) which is at the apex of the food chain. It is the only mangrove-tiger kingdom in the world and presently harbours 95 tigers in Indian Territory and 105 tigers in Bangladesh. The tiger leads an almost amphibious life and is an excellent swimmer. It has been seen to cross rivers as wide as 2 km at a stretch. It has adapted itself nicely to this difficult terrain which is characterised by sharp pneumatophores, muddy substratum, innumerable rivers and creeks with tidal rhythm, variable salinity and lack of freshwater source. The principal prey species of the tiger are spotted deer, wild boar and *Rhesus macaque* that also swim across the streams and water channels. In addition, it also feeds on fish, crab and water monitor. In one instance, a post-mortem of a dead animal revealed the presence of a Monocellate cobra and a King cobra from the stomach

Fig. 12.5 Royal Bengal Tiger (*Panthera tigris tigris*) of Sundarbans

of the animal. This is only one of the very few recorded instances of tigers eating King cobras. The man-eating traits of Sundarban tigers have become almost a legend in Bengal and elsewhere. It is considered that man-eating propensity of tiger in this area is an acquired trait over a period of generations given the harsh surrounding conditions. It has been noticed that in the last 10 years apart from one case where the tiger had accidently killed a girl, all the deaths have occurred inside the forest. This peculiarity in the tiger behaviour has been explained by various experts that within the forest area, i.e. their habitat, they consider all moving objects as their prey. It is generally believed that the tigers in this mangrove forest do not have territories due to the obliteration of urination marks by the tidal waters. However, this is yet to be borne out by scientific facts. Recent data from radio-collared tigers reveal that the animals are using specific areas possibly indicating territoriality.

Though the tigers may breed at any time of the year but in Sundarban it has been observed that the mating season starts in winter and continue up to March to April. During this period, males often fight with each other but there has never been any report of fatal fights in the Sundarbans. General gestation period of tiger is 95 to 110 days. In Sundarban, the litter size of 1 to 2 is very common and rarely three or more cubs have been sighted. Usually, cubs stay with their mother up to 2–3 years but in Sundarban it is seen that they are separated by the time they are two-years old approximately. Generally, inter-cub interval of tigress is approximately 3 years but not much observation has been made regarding Sundarban tigers due to difficult terrain and their man-eating propensity. Occasionally, up to five tigers have been sighted together in Sundarbans. This could be a case of the sub-adults with the male and female.

Based on the preliminary results of the radio telemetry studies in Bangladesh, Sundarban (Barlow et al. 2008) documented home range sizes for two adult females of between 12 and 15 sq. km. They also studied on the skulls of Bangladesh Sundarbans tigers and found that it is significantly different craniometrically from all other currently defined subspecies, both in terms of size and shape. This distinction was most notable for male tigers, which tend to have more variable morphology than females. These findings add to previous work on tiger craniometrics that found substantial differences between the mainland and Sundarban Island.

Apart from the tiger, the secondary predators are mainly the fishing cats (*Felis viverrina*) and to small extent the jungle cat. They feed on small birds, snakes, fish, etc. Among other ground dwelling fauna are Spotted Deer (*Axis axis*) and wild boar (*Sus scrofa*). The wild boars feed on underground tubers but also relish dead fishes, prawns, crabs, molluscs and sea turtle eggs. The Spotted Deer preferably browse on leaves, twigs and fruits of Keora (*Sonneratia apetala*), 'Bain' (*Avicennia officinalis*) and Genwa (*Excoecaria agallocha*).

The cetaceans like Gangetic Dolphin (*Platinista gangetica*) and the Irrawady Dolphin (*Orcellabre virostris*) are frequently found in the eastern side particularly in rivers like the Raimongal, Goasaba, Matla and the sea-facing areas. The Black Finless Porpoise (*Necmeris phoceanoides*) is also found in rivers near the estuary.

12.4.2.2.2 Reptiles

The estuarine crocodile (*Crocodylus porosus*) (Fig. 12.6) is the top-most predator in the aquatic ecosystem. Apart from the estuarine crocodile, the water monitor lizard (*Varanus salvator*) which reaching up to 2.4 m in length can be frequently found within the reserve. The sea-facing beach of the reserve forms a nesting ground for

Fig. 12.6 Estuarine crocodile (*Crocodylus porosus*) in Sundarbans

olive ridley sea turtle (*Lepidochelys olivacea*), which come to lay eggs on the sandy beaches of the Tiger Reserve. The egg laying is sporadic and takes place mainly during December to March. The water monitors are the greatest predators of their eggs and hatchlings along with wild boars, terns and sea gulls. The endangered River Terrapin (*Batagur baska*) also uses the beaches as their nesting ground. The Mechua beach in Bagmara block is an important nesting ground. Dr. A.K. Mukherjee of Zoological Survey of India (ZSI) has recorded other coastal soft-shell turtle (*Pelochels bibroni)*, Bengal eyed terrapin (*Morenia ocellata*) and three keeled terrapin (*Geomydatrica rinata*) from the area. Occasional reports of presence of green sea turtle (*Chelonia mydas*) and Hawksbill turtle (*Eritmochelys imbricata*) have also been received.

Since the 1980s, ex-situ conservation program was started and eggs of the turtles were collected from turtle pits and incubated at Sajnekhali. The hatchlings were subsequently released in the sea. This practice has been subsequently discontinued and now in-situ conservation of the turtle is carried out on the beaches. The egg pits are surrounded by wire meshes to prevent the eggs from being destroyed by the wild boars and water monitor lizards. After hatching, the wire mesh is removed and the hatchlings move out into the sea. Similarly, an ex-situ conservation program for the estuarine crocodiles is going on at Bhagbatpur. The crocodiles reared here are released into the tidal waters. This is an ongoing program.

Around 53 species of snakes are found in the area. Prominent among the poisonous are the king cobra, monocellate cobra, banded krait, Russell's viper, common krait. The python, chequered keelback, dhaman, green whip snake, ornamental snake and several other species constitute the non-venomous snakes. The tidal creeks also harbour Homalopsid snakes adapted to living in water, the most common being the *Cerberus rhynchops* or dog-faced water snake. Snake bite cases are very common in the fringe villages between July and October, especially due to cobra and krait.

12.4.2.2.3 Avifauna

There are over 200 species of birds, which have been recorded from the area. These include a large number of migrants from the higher latitudes that visit the area in winter. Heronries are developed during monsoons in Arbesi and Jhilla blocks. Common birds found in the area include herons, egrets, darters, spoonbills, cormorants, storks, etc., which come out and nest in the area. Earlier there was a heronry around Sajnekhali covering 1.5 sq. km area, which used to develop from June to end of September. However, this nesting ground suffered intense damage during the cyclone of 1988 and is no more active.

The bird species, which are most abundant in the Sundarbans Tiger Reserve, include the Purple Heron (Fig. 12.7), Adjutant Stork, Common Sandpiper, Indian Ringed Dove, Whimbrel, Tailorbird, Black-capped Kingfisher, Jungle Myna, Rose-ringed Parakeet, Large Egret, Bronzed Drongo, White-collared Kingfisher, Magpie Robin, Pond Heron, Common Iora and Red-vented bulbul. The mangrove is also

Fig. 12.7 Huge Purple Heron in Sundarban (photographed in April, 2020)

known as the kingfisher's paradise with 8 out of 12 species of kingfishers found throughout the country found here. Other birds found in the area are median egret, brahminy kite, white-bellied sea eagle, lesser adjutant stork, osprey, Goliath heron, whiskered tern, brown-winged gull, common sandpaper, jungle myna and rose-ringed parakeet.

12.4.2.3 Aquatic Community

The aquatic habitat has not yet been studied in full. However, some works have been done by Zoological Survey of India. The most interesting is the formation of Phytoplankton in the shallow clear water of the tidal creeks receiving enough sunlight for a luxuriant growth. The phytoplanktons are the sources of augmentation of oxygen content in the water. This influx, however, is checked by the zoo-plankton particularly by the shrimp population, which invades mangrove estuary during the semi-larval stage to adult stage. The zoo-plankton consumes the phytoplankton and diminishes the oxygen content and the whole equilibrium is also controlled by the seasonal salinity of the creeks. The total catch fish diminishes to a minimum during the highest salinity as has been recorded by Chaudhuri and Choudhury 1994. The micro-organisms, like *Noctuluca*, dinoflagellates produce bioluminescence during winter night particularly near the sea-face and entire atmosphere turns into a fairy land.

12.4.2.3.1 Fishes and Crabs

A wide and varied assortment of fishes, molluscs, crabs and prawns inhabits the estuaries. The mangrove leaves, which decompose slowly, offer food and shelter for the larval shrimps and they migrate from the sea to the mangrove estuary for attaining maturity. Even the snappers or mullets depend very much on the mangroves. Mullets like Bhetki and Bhangor constitute the main form, the edible fishes in the area. The studies of fish made by Chakraborty (1984) also reveal that *Pangasius pangasius* fiddler, i.e. Pangas fish is the primary heterotrophy, which often swallows full keora fruit. The amphibious crab mud skipper fish such as *Periophthalmus* and *Boleophthalmus* arouse considerable interest. The former creeps up the trees with the rising water level. Among the crustaceans, the one-armed (*Uca* species) often shows off to his mate with the colourful arm. They have diurnal clock inside which regulates their colour change along with tides. Another interesting crab is the *Clibanarius padavensis* (deman), i.e. Hermit crabs occupying gastropod shells of genus *Telescopium, Nerita, Cerithidea* or *Semifusus.* The edible crab *Scylla serrata,* is important as well as the ghost crab and patalchingri (*Thalassina anomala*). Marine borer like *Teredo* often causes concern to the watercrafts.

There are two species of trilobite, viz. *Tachypleus gigas* and *Carcinoscorpius rotundicauda* commonly known as Horse shoe crab or king crab. King crabs are now protected owing to its ability or high sensitivity to bacterial endotoxins. The cell lysates obtained from the blue blood of the species are widely used for estimation of bacterial endotoxin. They have hardly changed in 400 million years are also called living fossils. They visit Sundarbans during pre-monsoon season (March to June) when the salinity reaches its peak. During this season, they are found mating in mangrove creeks and mudflats. They are often killed by people owing to the belief that they can cure arthritis.

The fish fauna of the estuarine waters in and around the Sundarbans have been classified into residents and transients (migrants). The residents include *Mugil parsia*, *M. tade*, *Polynemus paradiseus*, *Polydactylus indicus*, *Otolithoides biauritus*, *Lates calcarifer*, *Hilsa toil*, *Arius jella*, *Harpodon nehereus*, *Ilisha elongata*, *Pama pama*, *Sillaginopsis panijus*, etc. The transient or migratory fish which enter the estuary for a short time mainly to spawn include *Tenualosa ilisha, Pangasius pangasius*, *Polydactylus indicus,* etc.

12.4.2.3.2 Sharks and Rays

The sharks and rays found in Sundarban include the Ganges shark (*Glyphus gangeticus*), Small-toothed saw fish (*Pristis microdon*), Pointed saw fish (*Anoxypristis cuspidata*) and white-spotted shovel-nosed guitar fish (*Rhynchobatus djiddensis*) all of which are Schedule-I species in the Wildlife (Protection) Act, 1972. In addition to these, the following are also found— *Rhinobatus granulatus, Himantura alcockii, Rhinoptera javanica, Sphryna zygaena,* etc.

12.5 Phytoplankton, Zooplankton and Microbial Diversity

12.5.1 Phytoplankton

Phytoplankton diversity is huge in mangrove areas. Diatoms form the predominant group in the mangrove habitat. The common diatoms identified are *Navicula* sp., *Pleurosigma* sp., *Gyrosigma* sp., *Cymbella* sp., *Cyclotella* sp., *Fragillaria* sp. and *Amphipleura* sp. The Cyanophyceae or Myxophyceae floras are *Oscillatoria* sp., *Lyngbya* sp., *Spirulina* sp., *Anabaena* sp., *Microcoleus* sp., *Nodularia* sp. and the Chlorophycean planktons are *Protococcus* sp., *Pediastrum* sp., *Hydrodictyon* sp. and *Ankistrodesmus* sp., while the common desmid is *Cosmarium* sp. The common benthic algal floras from this brackish water area of Sundarbans are *Oscillatoria* sp., *Gleocappa* sp*., Symploca* sp., *Protococcus* sp., *Enteromorpha* sp., *Polysiphonia* sp. and *Gyrosigma* sp. (Guha Bakshi et al. 1999).

The pneumatophores, knee roots, stilt roots, areal roots and the lower trunk regions of *Avicennia* sp., *Xylocarpus* sp., *Sonneratia* sp. and the members of Rhizophoraceae hold the dense cover of *Bostrychelium* like *Bostrychium* sp., *Caloglossa* sp. and *Catenella* sp. These periphytons have also much value as fish food in these mangrove swamps. Molluscs, crabs and other crustaceans are also dependent on these algal species in mangrove habitat as their natural food.

12.5.2 Zooplankton

Sundarbans mangrove ecosystem harbour heterogenous assemblage of innumerable invertebrates which are collectively called zooplankton. Zooplankton comprises diverse taxonomic groups mainly consisting of copepods, amphipods, ostracods, chaetognaths, mysids and hydromedusae. Pillay (1954), Chakraborty (1984) and others have pointed out that in Sundarban estuarine water, copepods are dominant representing usually more than 60% of the total zooplankton population. The important copepod species are *Diatomus* sp., *Pseudodiatomus* sp., *Acartia* sp., *Cyclops* sp. and *Cyclopsis* sp. Zoea and megalopa larvae, mysids are reported by Pillay (1954). Benthic animals produce millions of planktonic larvae which constitute staple food of mangrove associated fishes. Ciliates, Flagellates, Helminthes and Rotifers are found in this brackish water during the monsoon months which have much value for these euryhaline fish and prawn species. This way a definite ecological cycle having dependence between autotrophs and heterotrophs exists.

The heterogeneous communities of Zooplanktons play a significant role in trophic structure and energy transfer. Taxonomically, diverse benthic animals which mostly occupy littoral and sub-littoral zones of this ecosystem are also ecologically and economically very significant. Some of these benthic communities belonging to Mollusca and Crustacea comprise shellfishes which are having direct economic importance. Benthic animals produce millions of planktonic larvae to support fish population (Chaudhuri and Choudhury 1994).

12.5.3 Microbial Activity

Cyanophyceae group of algae normally grow and flourish well on the ill-consolidated saline- sedimented humus soil in the mangrove areas which are hydrophilic and biologically very active and able to bind the soil particles together in consolidated form. These blue-green-algae (BGA) accelerate the growth and wide coverage of Chlorophyceae. Chlorophyceae group of algae prefer mostly consolidated soils, rich in nitrate and phosphate. By the oxidation process of these Cyanophyceae algae, inorganic phosphate and ammonical radicals are released which later on converted to nitrates. On the other hand, the excreta and exuviae of the mangal biota enrich the silty clay soils on its upper layer with the gradual decomposition and deposition of inorganic nitrate, phosphate and other substances. All these nitrate molecules accelerate the active growth of the autotrophs. These surface soil layers within the depth of 5.0 cm are well oxygenated. The mangrove soils are also sticky and black coloured for the reduced state of ferric compounds to ferrous sulphides. This reduction process is initiated by the abundant hydrogen sulphides.

Numerous pores and burrows are formed on these consolidated tidal river flat soils and forest floors due to the activity of certain crustaceans, molluscs, nematodes and some fishes like *Boleopthalamus* spp., *Periopthalamus* spp., etc. Several biotic and abiotic factors of these tidal mangrove soil phases assist the microbial activities. In these highly saline river basin soils, the molluscan and crustacean shells and other organic detritus fertilise the soil for the effective growth of the mangrove herbs, shrubs and trees (Naskar and Guha Bakshi 1987). Higher percent of calcium ion (Ca^{2+}) in these tidal mangrove soils reduces the adverse effect of sodium ion (Na^{+}) taken in by the mangrove flora. *Porteresia coarctata* thrives well both in the less-consolidated and in consolidated sedimented soils on the river flats. This halophytic grass can stand higher soil and water salinity and send its pseudo-tap roots to the deeper soil layers and afterwards its wide spreading fibrous roots anchor firmly on these loosely sedimented soils. Schuster (1952) stated that bacteria, blue-green-algae, green algae and diatoms act as nitrogen-fixing and sulphur-reducing agents in these alluvial tidal mangrove soils.

12.6 Mangrove Dependence and Livelihoods

12.6.1 Socio-Economic Profile of the Villages

The fringe villages have a high percentage of socially disadvantaged groups like Scheduled Castes 32% and Scheduled Tribes 12%. The level of literacy as well as per capita income is much lower in Sundarbans than in other parts of West Bengal. The tribal population here is the descendent of the group of tribes of Chottanagpur, who were brought here for clearing the areas for human settlement during the nineteenth century. In the absence of any major industry in the area, the vocation can be divided as cultivators 26.5%, agricultural labour 47%, household worker 1.5% and others 25% which include fishermen, crab collectors, honey collectors, etc. The majority of the farmers fall under the category of small and marginal farmers.

The village-rich mainly invests in agricultural land and commercial fishing, by engaging the poor fishermen to earn high profits. Moneylenders also abound in the villages. They give advances to fishermen and honey collectors in return of which they take all the fish catch and honey collected from the fishermen/honey collectors for a pittance. Most of the villagers also have cattle population, which are reared not for milk supply but to fulfil their protein requirements. Most of the cattle are stall fed or are left out in the local fields and the Tiger Reserve does not have grazing problems due to village cattle as is seen in other parts of the country. Prawn fishery has become a very popular trade by regulating the tidal water flow inside low-lying fields and farm land outside the reserve.

The infrastructure in the villages is poorly developed with hardly any metalled roads. The kutcha roads become very slippery during the rains making it very difficult to walk there. There is no electricity in the area. The wood gassifier plant at Gosaba having capacity of 500 kW was established in 1996–1997 by the West Bengal Renewable Energy Development Authority (WBREDA) and supplies electricity to some parts of the Gosaba Island. Though, the demand for the raw material is met from the wood growing in the local areas, still it faces a perpetual shortfall in supply of wood. The rest of the area is steeped in darkness. Individually some of the families have availed of subsidy by WBREDA to get solar lights installed in the village. Mode of communication in this area is mainly country boats and mechanised boats and the speed of which is regulated by the movement of the tidal currents. Concrete jetties which are boarding and disembarking points for people boarding watercraft are few and far between and at many places still brick block jetties are used to board boats. Primary health centres and schools are also not adequate. The local markets are called ‘haats’ and are organised once a week where the villagers come from far off places to buy and sell agricultural and other produce.

12.6.2 Resource Dependence of the Villagers

The lack of industries coupled with high population density have led to a high level of resource dependency (Ellison 2008). Dire poverty is the primary reason for people venturing into the forests braving risks like man-eating tigers and other fierce animals, frequent cyclones and storms. Every year some of these people who enter the forest fall prey to the tiger. They enter the mangrove forests for fishing, honey and fuel-wood collection. However, many miscreants often take the guise of fishermen and enter the forests with the intention of poaching and felling of timber species. Though in the past people would enter the forest for collection of *Nypa fruticans* (golpata) and *Phoenix paludosa* (hental) leaves which are used for thatching. These practices have since been discontinued.

12.6.2.1 Fuelwood and Timber Collection

The people in many border areas especially the eastern sector used to enter the Tiger Reserve to collect fuelwood and at times timber species also. The main species collected were *Ceriops decandra* locally called as Goran. The sticks from these trees were used for fencing purpose and thicker ones for posts of houses. In addition to these, *Avicennia* sp. which also have high calorific value were also cut. Most of the mangroves have little timber value except *Xylocarpus* and *Heritiera* sp. Presently these activities have been totally stopped inside the tiger reserve. In Arbesi Block under Jhingakhali beat of Basirhat Range, due to the silting up of the demarcating khal called the Shakunkhali and during low tide, the forest and village side are separated by a distance of only 2–3 m at some places. Although, a nylon net fencing separates the forest from the village area all along Arbesi 1, there is a tendency of the people to cut the net to gain entry into the forest. This often leads to man-animal conflict scenarios.

12.6.2.2 Fishing

Fishermen enter into the STR area for fishing after getting permits from the office of Sundarban Tiger Reserve. These permits are given for a specific time and area as mentioned in the permit. These permits are issued against registered Boat Licence Certificates or BLC's. Presently in Sundarban Tiger Reserve, there are about 923 Boat Licence Certificates or Fishing Permits, out of which three quarters are active and one quarter are lying inactive due to various administrative and technical reasons. However, some irregularities have been noticed like the fishermen usually extend their period of stay in the forest area and try to enter non-permitted areas.

12.6.2.3 Tiger Prawn Seed Collection

It is a much profitable livelihood activity. This livelihood has been heavily discouraged due to its negative impact on the ecosystem. Presently after formation of Joint Forest Management Committees (JFMCs), only a handful of people are involved in this activity.

12.6.2.4 Honey Collection

Rock bees (*Apis dorsata*) from the Himalayas visit the Sundarbans Forest every year. Most of the mangrove flowers are highly nectar bearing. This attracts the rock bee to visit Sundarbans during summer months which is the main flowering season. Flowering starts with the bloom of *Aegiceras corniculatum* at the end of March and is followed by the flowering of *Acanthus ilicifolius, Avicennia* spp., *Sonneratia apetala, Rhizophora* spp. This continues for 2 months from April to May. The density of honey depends on the number of salt-excretory glands available on the tree. Khalsi (*Aegiceras corniculatum*) having 19 glands per sq. mm. gives the best honey. As rock-bees are migratory, so the experiment of setting up apiaries has failed. The honey from Khalsi is considered to be the best in quality. The Goran produces the maximum and the minimum is obtained by Gnewa (*Exoecaria* spp.). It has been found that Gnewa bears about 39% of honey comb and Bain (*Avicennia* spp.) 16%, Goran (Ceriops spp.) 11%, Garjan (*Rhizophora* spp.) 10% and others bear only 24%. The ideal site for construction of hive would be Hental-Gnewa combination forests. Honey Collection is a very important activity in Sundarbans. A lot of people are involved in honey collection which is facilitated by the Forest Department. The collection of honey begins from the month of March to April and continues for about two to three months. This is the time when most of Sundarban flora is in full blossom. Permits are issued to the honey collectors after the minimum support price is decided by a joint meeting of the Sundarban Tiger Reserve management and West Bengal Forest Development Corporation. Each permit allows 6–10 people enter the forest areas. During this period, fishing is stopped. Floating camps are put up with armed staff equipped with RT sets, speed boats, etc. are placed in different places to keep a watch and ward over the entire activity and to attend to the emergencies like tiger attack, snake bite, etc.

12.6.2.5 Ecotourism

Sundarbans are rich in flora and fauna. Ecotourism is catching up rapidly in Sundarban areas. Main tourist season is from October to February though tourists visit Sundarbans throughout the year. Some people are engaged in hotel/resort business, some are engaged in supply boat/launch to tourists and some are engaged as tourist guide. They earn a good amount during tourist season.

12.7 Threats and Conservation

The mangroves of the Sundarbans are endangered and are in alarming state due to present trends of over exploitation and the large–scale dependence of huge rural population of the Lower Gangetic Delta. Besides this, the recently changed geological events, viz., neotectonic movement of the Earth and change of upstream fresh water flow towards east of the river Hugli (The Ganga) have changed the Sundarban mangroves to a great extent. These mangrove ecosystems are used for developing prawn and fish farm. Indiscriminate shrimp seed collection has led to damage to other indigenous shrimp, fish juveniles and planktonic population. The uncontrolled harvesting of exportable mud-crab and alarming trend of wood cutting also possess threat to mangroves of Sundarban. There are also threats to many species like spotted deer, wild boar, water monitor lizard, Olive Ridley turtles and sometimes tiger for poaching. Poachers in Sundarbans use many techniques like nylon rope traps, steel wire traps, gun shots, poisoning, etc. to poach the target animals. There are clandestine local markets for deer and boar meat. Olive Ridley turtles are also poached by fishermen because of their meat. The drainage of hydrocarbons from ships and other marine vessels leads to development of pathogenic microbes which infect the free living and cultivable aquatic life forms. This causes serious setback to cultivation and production of dollar earning species. With the adoption of Joint Forest Management with People's participation, the protection and management of mangrove flora and fauna of Sundarbans have improved a lot. This has been possible due to involvement of local people in Forest Reserve management, decision making, conducting entry point activities and ecodevelopment activities, study tour to the successful JFM areas.

12.8 Conclusion

Sundarbans is one of the biodiversity rich sites in the world and it is the privilege of this region to have such a wonderful wildlife habitat. Now it is felt necessary to conserve the Sundarban ecosystem in its natural state so that several natural calamities can be averted and can be helped to check the atmospheric pollution. The wild lives of the mangrove forests also help to maintain the ecological balance as the plants and animals are directly interdependent on each other. The tigers in land and the crocodiles in the water in Sundarbans are the two top consumers in a closed ecosystem. Hence, their presence is very much necessary to keep in control the ecological flow by the sustained growth of another biota. The rivers and creeks of Sundarbans are the nursery ground of numerous fishes including economically important tiger prawns (*Penaeus monodon*). With the increasing population pressure, the ecosystem of the Sundarbans is losing its balance slowly. As a result of our inordinate hunger and personal greed and owing to our laziness, the present-day environmental degeneration has come into being and repair of the same can be possible by our efforts only. Environment and ecology cannot be preserved unless the need-based planning for maintenance of life and living of the inhabitants of the Sundarbans is taken up together.

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Chapter 13
Sri Lankan Mangroves: Biodiversity, Livelihoods, and Conservation

Sriyani Wickramasinghe, Malaka Wijayasinghe, and Chaya Sarathchandra

Abstract Mangroves in Sri Lanka occur in a patchy distribution along the island's coastline, in areas adjacent to lagoons, estuaries, and river mouths covering an area of 16,017 ha. Twenty-one species of true mangroves and 18 mangrove associates are recorded, while 214 vertebrates comprising of 112 species of ichthyofauna, 2 species of Amphibia, 13 species of Reptilia, 72 species of Avifauna, and 15 mammal species are found in the mangrove forests. Local communities settled near mangrove areas are heavily dependent on mangroves for their livelihood; branches of *Avicennia* spp. are used for brush pile traditional fisheries; tender leaves of *Avicennia marina*, *Sonneratia caseolaris*, *Acrostichum aureum*, and *Suaeda maritima* are used as food. Wood of *Cerbera manghas* is used to carve masks and puppets, while *Nypa fruticans* is used to make alcohol, sugar, and vinegar. Overexploitation of mangrove products, habitat destruction for development, pollution, spreading invasive alien species, climate change, and global warming are some of the threats to the mangrove ecosystem in Sri Lanka. Successful restoration practices are carried out in Kalpitiya, Pambala, and Negombo. Approximately 1000–1200 ha of mangroves have been planted in 23 sites in Sri Lanka. Sri Lanka claims to be the first nation in the world to protect all its mangroves, making it illegal to cut down them anywhere in the island, and the first to open a mangrove museum (in Pambala, Chilaw). Sri Lanka has also been named as a leader for the conservation of mangroves in Commonwealth countries.

Keywords Patchy distribution · Local communities · Traditional fisheries · Restoration · Mangrove museum

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13.1 Introduction

The exact extent of mangroves is yet to be verified formally, but recent investigations carried out by the Department of Forest have revealed an extent of 16,017 ha of mangroves in Sri Lanka (Fig. 13.1). The major mangroves in Sri Lanka are located around Jaffna, Vadamarachchi, Thondaimanaru lagoons (northern coast), Kokkilai, Navarau lagoons, Trinkomalee, Kathiraveli, Valaichenai, Batticaloa, Pottuvil (eastern coast), Weligama, Gintota (southern coast), Balapitiya, Bentota, Negombo and

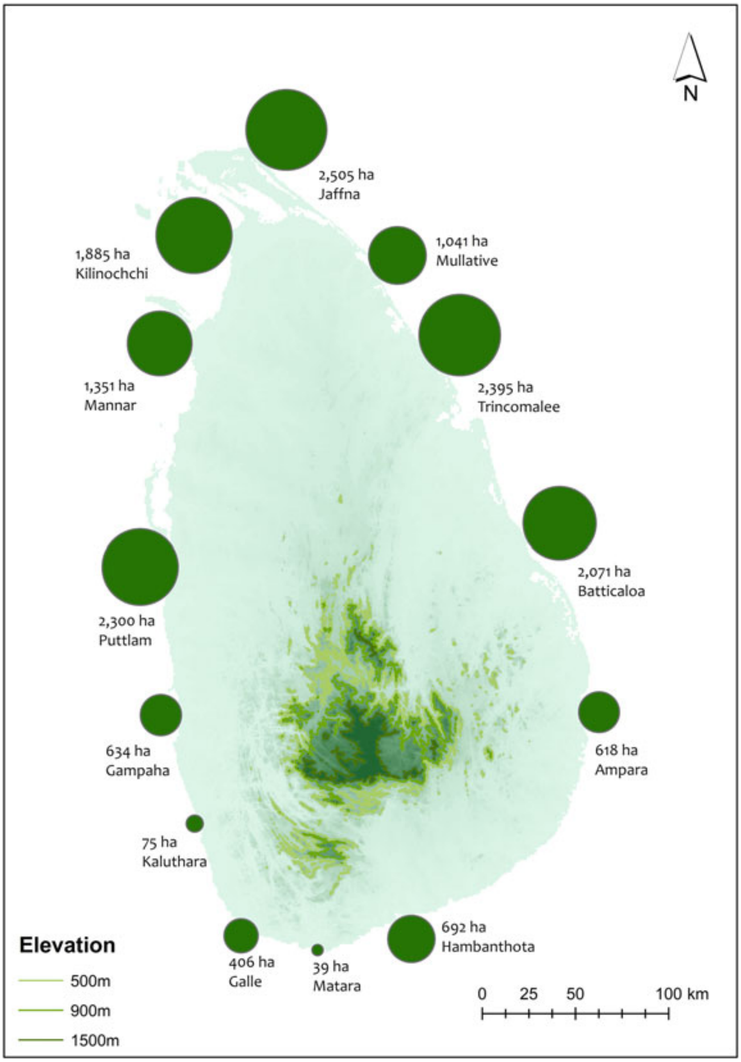

Fig. 13.1 Extent and distribution of mangroves along the coastal region of Sri Lanka

Chilaw lagoons, Puttalam lagoon, and Mannar (western and northwestern coasts) (Ranawana 2017). Most of the mangrove patches are small in extent, disjointed, and disturbed, but a few relatively undisturbed mangrove patches with a considerable extent (>1000 ha) are found in northwestern (Gangewadiya), northern (Vidattaltivu Nature Reserve), and northeastern (Gangi, Upparu in Mahaweli river mouth) coastal belt (MoMD & E 2019).

13.1.1 Dynamics of Physiochemical Characteristics

Five types of mangroves, namely, riverine, fringing, scrub, over wash, and basin, have been identified in the island. This classification was based on the topography, flooding characteristics, and floristic composition (Balasubramaniam 1985). Many factors strongly influence the occurrence and growth of mangroves, and these include geographical latitude, wave action, rainfall, freshwater runoff, erosion/sedimentation rates, acidity, salinity, nutrient inputs, and soil quality (Perera et al. 2013). Research findings of Cooray et al. (Cooray et al. 2021) highlighted that soil pH, salinity, organic matter, K, Mg, Ca, Cu, Ni, Zn, and Mn were identified as fundamental soil chemical properties that preserve and support mangrove vegetation. In return, tree density, tree height, stand basal area, tree biomass, and vegetation complexity sustained the soil as primary forest structural attributes.

Kodikara et al. (2017) highlighted some physicochemical characteristic of mangroves in different climatic zones (Table 13.1), while De Silva and De Silva (1998) reported physicochemical characteristic of some mangroves (Table 13.2). The average air temperatures prevailing in the mangrove forests range from about 30 °C to 35 °C. The relative humidity is very high and ranges from 80% to >90%. The mean surface water temperature of the Negombo Lagoon was within the range of 29.8–30.1 °C, with seasonal temperature difference of 3–6 °C, as reported by Silva and De Silva (1981) and Rajapaksha 1997, respectively.

Table 13.1 Climate data and distribution of true mangroves with respect to different climatic zones (Source: Kodikara et al. 2017)

Climate zone	Mean annual rainfall (mm)	Average annual temperature (°C)	Tidal amplitude (ppt)	True mangrove species
Dry	<1750	31.5	0.4–0.6	11
Wet	>2500	28.5	0.5	10
Intermediate	1750–2500	30.0	0.5	16
Arid	<1250	32.5	0.4–0.6	11

Table 13.2 Some important physicochemical characteristics of water in selected mangrove forests (Source: De Silva and De Silva (1998))

Location	Climatic zone	Mangrove type	Temperature (°C)	pH	DO ppm	Salinity (ppt)
Negombo	WZ	HS/LS	27–31	7.5–8.3	4.6–8.7	18–32
Bentota	WZ	LS	26–30	6.1–7.2	5.1–8.8	0–8
Balapitiya	WZ	LS	26–31	6.4–7.6	4.1–8.1	0–6
Koggala	WZ	LS	27–32	6.6–8.2	4.5–9.2	0–12
Rekawa	WZ	HS	29–34	6.2–7.4	6.3–10.6	18–34
Ranna Oya	WZ	LS	28–32	6.2–7.3	5.2–8.3	3–9
Kalametiya-Lunama	WZ	LS	28–32	7.5–9.2	4.0–8.5	0–6
Menik River	DZ	HS	27–33	7.1–8.3	4.1–7.9	0–26
Kumbukkan Oya	DZ	LS	27–33	7.1–8.2	4.3–8.0	0–18
Batticaloa	DZ	HS	27–34	6.9–8.3	3.9–7.8	6–34
Mannar	DZ	HS	28–42	6.9–7.9	3.1–7.5	2–36
Kalpitiya	DZ	HS	28–41	7.3–8.2	3.1–8.1	21–36
Kala Oya	DZ	HS/LS	27–31	7.1–8.1	3.5–7.4	0–28
Mee Oya	DZ	HS/LS	27–31	6.9–8.1	4.1–8.3	0–25
Mundel	DZ	SC	27–35	7.1–8.4	4.5–9.1	15–45

DO dissolved oxygen, *WZ* wet zone, *DZ* dry zone, *HS* high salinity, *LS* low salinity, *SC* scrub

13.1.1.1 Soil and Sediments

The lagoons and estuaries contain alluvial deposits, and the soil consists mainly of silt and fine clay, although in some areas, sandy soil is found. The soil is waterlogged and consequently poorly aerated; in some locations, there is stagnant water (Perera and Amarasinghe 2019). The density of mangroves affected the granulometry and chemistry of accreting sediment and the belowground biomass of the trees. Sediments with finer textures also usually have higher nutrient concentrations, partly because of their greater ability to bind nutrients onto particle surfaces and within interstitial spaces (Phillips et al. 2017).

13.1.1.2 Salinity

The salinity in mangrove waters could vary from almost nil to more than that of seawater. Salinity depends mainly on the pattern and amount of freshwater discharge from nearby rivers, the tidal amplitude, and the topography and the extent of the estuary or lagoon. The salinity of Negombo Lagoon is strongly related to the monsoon rains (Silva and De Silva 1981; Rajapaksha 1997). The floristic composition and the species distribution of the mangrove depend on the level of salinity. In Kala Oya estuary, the *Avicennia marina* was the most salinity-tolerant species (13.25–23 mg/l) followed by *Rhizophora mucronata*, *Ceriops tagal*, and *Lumnitzera* *racemosa* (8 mg/l). *Excoecaria agallocha* was the least salt-tolerant species in the area (Perera et al. 2013). Further, this study showed that the soil salinity of 13 mg/l supports the highest mangrove species richness in the Kala Oya estuary. This might be the most favorable salinity regime for the majority of mangrove species of this area. Cooray et al. (Cooray et al. 2021) showed unlike other mangrove species recorded in Vidattaltivu, *Avicennia marina* thrived in elevated salinities (4.36–20.16 ppt).

13.1.1.3 Total Organic Carbon (TOC)

Mangroves are supreme agents in building blue carbon pools by capturing atmospheric carbon and storing them in biomass and soil. Anaerobic mangrove soils favor accumulation of partially decomposed organic matter that builds the carbon stocks over time. In the majority of mangrove areas, TOC stocks increased with depth and across the water-land gradient. An estimated magnitude of the carbon pools in Sri Lankan mangrove soils ranges from 316.29 to 580.84 Mg ha^{-1}. Mangrove soils of Rekawa Lagoon, located in the intermediate climatic zone, were found to be the largest soil carbon sink (580.84 Mg ha^{-1}) while that of Batticaloa Lagoon in the dry zone was the smallest (316.29 Mg ha^{-1}). TOC storage in mangrove soils depends on the annual rainfall of the country (Perera and Amarasinghe 2018).

The amount of total organic carbon (TOC) content embedded in plant biomass was calculated to be 158.57 Mg C ha^{-1}, out of which 131.60 Mg C ha^{-1} was in the aboveground and 26.96 Mg C ha^{-1} in the belowground parts of plants. The total standing biomass (298.71 Mg ha^{-1}) of mangrove ecosystems in the Batticaloa Lagoon therefore is greater than that in the Negombo estuary (163.72 Mg ha^{-1}) located in the wet zone (Perera and Amarasinghe 2018) and that in the Rekawa Lagoon (62.4–201.8 Mg ha^{-1}) situated in the intermediate climatic zone (Dayarathne and Kumara 2013).

13.1.1.4 pH and Redox Potential

Soil pH and redox potential were measured in dry, wet, intermediate, and arid zones. Soil pH for the mangrove soils in these zones ranged from 7.1 to 5. Mangrove soil in the wet zone showed significantly lower pH values as compared to the other zones. Redox potential at 30 cm ranged from +6 to -146 mV in all zones and was relatively higher in the intermediate and wet zones than in the dry and arid zones (Kodikara et al. 2017). However, in Vidattaltivu mangrove (dry zone), soil redox potential values ranged between 14.30 mV and $-$ 39.80 mV, and pH values range from 4.64 to 7.29 (Cooray et al. 2021). Cooray et al. (Cooray et al. 2021) showed that the concentrations of most plant micronutrients (except Cu) decreased with increasing soil pH.

13.2 Floral Biodiversity of Mangroves in Sri Lanka

The total extent of mangroves in Sri Lanka was 15,670 ha (Edirisinghe et al. 2012) but has recently been revised to 15,981 ha (Arulnayagam et al. 2021) and 19,726 ha by the Forestry Department (Piyasiri et al. 2017). These mangroves are mostly associated with lagoons and estuaries in the coastal area of the country, and as a result, sparse distribution can be seen (Figs. 13.2 and 13.3). Distribution of mangroves is mostly in Jaffna, Trincomalee, Batticaloa, and Puttalam districts and to a lesser extent in southern coastal districts. In Sri Lanka, mangroves are usually limited to narrow belts because of the low (75 cm) tidal amplitude (Ranawana 2017; Karunathilake 2003).

Mangrove plant species are of two types, "true mangroves," species that are strictly limited to the mangrove environment, and "mangrove associates," species that are mainly distributed in a terrestrial or aquatic habitat but also occur in the mangrove ecosystem (Tomlinson 1994). The exact number of true mangrove species in Sri Lanka is erratic due to conflicting number of species reported in the literature by different authors which ranges from 16 to 29 species (Amarasinghe 1996; Arulchelvam 1968; Jayatissa et al. 2002; Jayatissa 2012). However, 21 true mangrove species (Table 13.3) are widely accepted (Jayatissa 2012). The most common and widely distributed are *Avicennia marina*, *Rhizophora mucronata*, *R. apiculata*, *Bruguiera gymnorhiza*, *B. sexangula*, *Excoecaria agallocha*, *Sonneratia caseolaris*, *Aegiceras corniculatum*, and *Lumnitzera racemosa* whereas *L. littorea*, *Xylocarpus granatum*, and *Scyphiphora hydrophyllacea* have limited distribution.

The exact number of mangrove associate species is also ambiguous due to conflicting reports, for example, Jayatissa et al. (2002) listed 18 mangrove associates which included *Acanthus ilicifolius*, *Acrostichum aureum*, *Cynometra iripa*, and *Xylocarpus rumphii* while some authors considered these species as true mangroves (Amarasinghe 1996; Arulchelvam 1968). Karunathilake (2003) mentioned that more than 25 plant species can be identified as mangrove associates and it depends on the edaphic and climatic factors of the habitat.

Based on the distribution of annual rainfall, Sri Lanka is mainly divided into three different climatic zones, namely, dry, wet, and intermediate. Interestingly, uneven species distribution is recorded by different authors within these climatic zones. For instance, the number of true and associate mangroves in the intermediate zone is 16 and 10, respectively. However, the number of true and associate mangroves in the wet or dry zones is 10–11 and 12–14, respectively (Jayatissa et al. 2002; Kodikara et al. 2017). However, Prasanna et al. (2017) have done a survey completely in the dry zone of the country covering 786 km (76% of the total mangrove area in the country) and reported 18 out of 21 true mangroves with the other three species confined to wet and intermediate zones.

Fig. 13.2 Flowering mangroves in Sri Lanka. (Mangrove associates: *Dolichandrone spathacea*, *Ardisia elliptica*, *Clerodendrum inerme*, *Cynometra iripa*, and *Acanthus ilicifolius*). (Photo courtesy: Gehan Jayasuriya and Malaka Wijayasinghe)

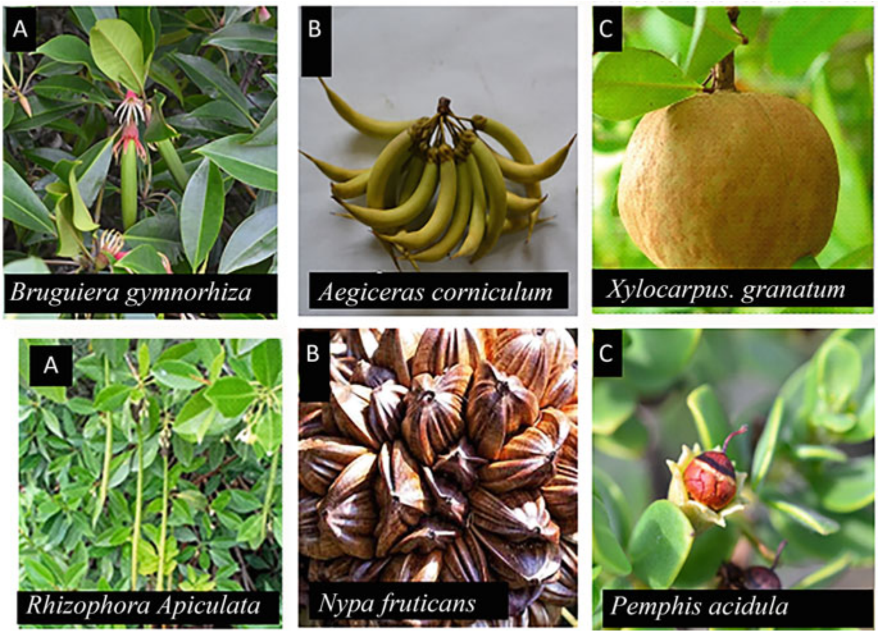

Fig. 13.3 Different types of fruits of true mangrove species in Sri Lanka according to their germination behavior: (**a**) true viviparous, (**b**) crypto-viviparous, and (**c**) non-viviparous (Photo courtesy: Gehan Jayasuriya and Malaka Wijayasinghe)

13.3 Faunal Biodiversity of Mangroves in Sri Lanka

13.3.1 Mangrove Fauna

Mangrove ecosystems are unique as they provide a variety of habitats for both invertebrate and vertebrate groups and provide nesting, breeding, and feeding grounds to a variety of marine and brackish species. The diversity of fauna in Sri Lankan mangroves is immense but is relatively poorly studied (Priyadarshani et al. 2010). However, a total of 99 invertebrates and 214 vertebrates have been reported so far, although most studies have been concentrated on the southwestern coast with Negombo as a hotspot for mangrove research (Arulnayagam et al. 2021).

13.3.1.1 Invertebrate Fauna

The mudflats of the mangrove forests are supporting various types of invertebrates including phylum Nematoda, Annelida, Mollusca, and Arthropoda. A total of 99 invertebrates dominated by 55 species of Arthropoda, and 26 species of Mollusca, with Nematoda ($n = 17$) and Annelids ($n = 26$) species, is also recorded from different mangrove sites in Sri Lanka (Arulnayagam et al. 2021).

Table 13.3 List of true mangrove species in Sri Lanka (Source: Jayatissa 2012) and their viviparity

Family	Species	Viviparity
Avicenniaceae	*Avicennia marina*	Crypto-viviparous
	Avicennia officinalis	Crypto-viviparous
Combretaceae	*Lumnitzera littorea*	Non-viviparous
	Lumnitzera racemosa	Non-viviparous
Euphorbiaceae	*Excoecaria agallocha*	Non-viviparous
	Excoecaria indica	Non-viviparous
Lythraceae	*Pemphis acidula*	Non-viviparous
Meliaceae	*Xylocarpus granatum*	Non-viviparous
Arecaceae	*Nypa fruticans*	Crypto-viviparous
Primulaceae	*Aegiceras corniculatum*	Crypto-viviparous
Rhizophoraceae	*Rhizophora apiculata*	Viviparous
	Rhizophora mucronata	Viviparous
	Bruguiera cylindrica	Viviparous
	Bruguiera gymnorhiza	Viviparous
	Bruguiera sexangula	Viviparous
	Ceriops decandra	Viviparous
	Ceriops tagal	Viviparous
Rubiaceae	*Scyphiphora hydrophyllacea*	Non-viviparous
Sonneratiaceae	*Sonneratia alba*	Non-viviparous
	Sonneratia caseolaris	Non-viviparous
Sterculiaceae	*Heritiera littoralis*	Non-viviparous

13.3.1.2 The Crab Fauna (Crustacea: Brachyura)

Out of 55 species of Arthropoda, crabs (Crustacea: Brachyura) are the dominant macrofaunal group (Table 13.4); 19 crab species from family Ocypodidae, Grapsidae, and Portunidae are recorded common in all large mangrove forests. In the muddy mangrove islets, there are numerous species of terrestrial crabs, commonly called mud crabs belonging to the family Grapsidae, which include *Chiromantes* spp. (mud crab), *Neosarmatium* spp., and *Neoepisesarma* spp. (De Silva and De Silva 1998). Most of the organisms in the mangrove swamp are burrowers, and they help to recycle nutrients, bringing subsoil to the surface, while feeding. *Neosermatium smithi* make complex burrows, but when the burrows are flooded, they build mud turrets reinforced by a stem of a small tree, so that they could maintain the burrow environment above the ground. *Neosermatium malbaricum* make T-shaped burrows, so that they can run into either branch of the burrow to avoid danger. *Chiromantes darwinensis* and *Chiromantes indiarum* often do not make neat burrows but find refuge in the crevices of puddles. The crabs of the family Ocypodidae, the fiddler crabs, occur on mudflats. *Uca dussumieri* and *Uca lacteal* were recorded from several mangrove forests in Sri Lanka. They all disappear into their burrows at the slightest shadow of danger. Another ocypodid, *Macrophthalmus*

Table 13.4 List of crab species recorded from Sri Lankan mangroves

Class	Order	Family	Species name	English name
Malacostraca	Decapoda	Grapsidae/ Sesarmidae	*Episesarma versicolor*	Violet vinegar crab
			Metopograpsus thukuhar	Thukuhar shore crab
			Metopograpsus messor	Tree climber crab
			Perisesarma guttatum	Red-claw mangrove crab
			Neosermatium smithi	Red spider crab
			Neosermatium malbaricum	
			Chiromantes darwinensis Sesarma (Chiromantes) darwinensis	
			Chiromantes indiarum Sesarma (Perisesarma) indiarum	
		Ocypodidae	*Uca [Tubuca] dussumieri*	Dussumier's fiddler crab
			Uca lactea	Fiddler crab
		Portunidae	*Portunus sanguinolentus*	Three-spot swimming crab
			Portunus pelagicus	Blue swimmer crab
		Portunidae	*Scylla serrata*	Mud crab
			Thalamita crenata	Spiny rock crab
		Varunidae	*Pyxidognathus deianira*	
		Thalassinidae	*Thalassina anomala*	Scorpion mud lobster
		Paguridae	*Eupagurus* sp.	Hermit crabs
	Isopoda	Sphaeromatidae	*Spheroma verrucauda*	

Sources: Arulnayagam et al. 2021, Sarachchandra et al. 2018, Jayasingham 2008, De Silva and De Silva 1998

depressus, is also found on these mudflats but prefers to remain submerged, with its long-stalked eyes above water, scanning the environment, as a submarine periscope.

The fiddler crab *Uca* spp. is found in mudflats within as well as outside the mangrove forests (De Silva and De Silva 1998). Males swing their large colorful claw to attract the females, but often females pay little attention. They all disappear into their burrows at the slightest shadow of danger. Hermit crabs *Eupagurus* sp. and *Pagurus* sp. were seen in all mangrove forests. The portunid crab *Scylla serrata*, which is commercially important in Sri Lanka, was found ubiquitously in all lagoons and estuaries examined but is especially common in Kalpitiya lagoon, eastern province, Negombo, and Chilaw (Sarathchandra et al. 2018; Jayasingham 2008; De Silva and De Silva 1998). The Anomuran *Thalassina anomala* (scorpion mud lobster) was seen in Mannar, Kalpitiya, Mi Oya, Kala Oya, and Negombo and Batticaloa mangrove forests.

13.3.1.3 Other Crustaceans

Twelve species of prawns and shrimps have been recorded from mangrove-associated habitat in Sri Lanka. Several species of peneid prawns were seen in lagoons and estuaries, of which the common species of commercial importance were *Penaeus indicus* (Indian banana prawn), *P. semisulcatus* (green tiger prawn), *Metapenaeus dobsoni* (Kadal shrimp), and *P. monodon* (tiger prawn). *Penaeus semisulcatus* is common in Kalpitiya area but is rare in the wet zone. *Macrobrachium* spp. (family Palaemonidae) is common in the estuaries of both dry and wet zones; *Metapenaeus rosenbergii* is the commonest species, but *Metapenaeus scabriculum* is also frequent. Atyid shrimps such as *Atyopsis spinipes*, *Caridina zeylanica*, *Caridina propinqua*, and *Caridina gracilirostris* were also recorded (De Silva and De Silva 1998; Jayasiri and Haputhantri 2015; Jayasingham 2008).

13.3.1.4 Mollusca

The most abundant bivalve families are Mytilidae and Veneridae. The bivalves, *Anadara* spp., *Geloina ceylonica*, and *Gafrarium tumidum*, are common in the mud in the shallow lagoons and estuaries in the dry zone and are found among sea grasses and occasionally within mangrove forests. The oysters, *Crassostrea* spp., are seen attached to the submerged roots of *Rhizophora* spp., etc. and in the shallow regions of all lagoons and estuaries. *Perna* spp., *Marcia* spp., *Pinna bicolor*, and the gastropod *Pleuroploca trapezium* were found in the lagoons and estuaries of the dry zone. *Littorina scabra* and *Nerita polita* are found in both the wet and the dry zone mangrove forests (De Silva and De Silva 1998; Jayasiri and Haputhantri 2015; Jayasingham 2008).

13.3.1.5 Polychetes

Polychetous annelids representing 16 families and 36 species (*Erantia*, 22 spp.; *Sedentaria*, 14 spp.) constituted 40% of the total macrofauna in Negombo Lagoon (Dahanayaka et al. 2008). Families with highest species richness are Nereididae (7 spp.), Peloridiidae (3 spp.), and Spionidae (3 spp.). Pilargidiids and Heterospionids are dominated in most of the areas of the lagoon. Low diversity or absolute absence of polychete was recorded from the mouth region and deeper areas of the middle region of the lagoon.

13.3.1.6 Zooplankton

Copepods and nauplii are common in the zooplankton of all lagoons and estuaries. However, some differences in the zooplankton in the wet zone and dry zone lagoons and estuaries were observed. In dry zone lagoons such as Kalpitiya and Batticaloa, the dominant zooplankton are *Caprella* spp. and *Noctiluca* spp., while *Ceratium* spp., Dinoflagellata, Cladocerans, and rotifers are dominated in the wet zone lagoons such as Negombo Lagoon (De Silva and De Silva 1998; Jayasiri and Haputhantri 2015). Only three locations have been studied so there is a limitation in assessing microfaunal diversity, and the reason for such a drop is still unknown.

13.3.2 Vertebrates

There are 214 vertebrates comprising 112 species of ichthyofauna, 2 species of amphibian, 13 species of reptilian, 72 species of avifauna, and 15 mammal species (Arulnayagam et al. 2021). The vertebrate fauna mainly depends upon the composition of the fauna of the surrounding area as most mangrove forests in Sri Lanka are rather restricted in size.

13.3.2.1 Ichthyofauna

Much of the ichthyofaunal community associated with estuaries are marine, followed by brackish and then freshwater species. Within Sri Lanka, mangroves also act as nursery grounds for marine species that are economically significant to the national fishing industry (Sarathchandra et al. 2018). Mugilids, carangids, cichlids, siganids, centropomids, and gobiids are a few of the common estuarine fish species associated with mangrove forests found in lagoons and estuaries as well as over 150 recorded species within mangrove forest-associated lagoons and estuaries (De Silva and De Silva 1998). Despite the existence of many common species depending on the prevailing salinity, the fish fauna differs somewhat in the wet zone and dry zone estuaries and lagoons. Glass eels and juvenile eels are also seen within the waters among the prop roots of *Rhizophora* spp. Bambaradeniya et al. (Bambaradeniya et al. 2002a) recorded some endemic fish species, namely, Sri Lanka filamented barb (*Dawkinsia singhala*) and near-threatened Sri Lanka walking catfish (*Clarias brachysoma*) and threatened Horadandia (*Horadandia atukorali*), from Maduganga mangrove areas. The mudskipper *Periophthalmus koelreuteri* is a regular occurrence on mudflats and among the prop roots of *Rhizophora* spp. in both the wet and dry zone mangroves (Fig. 13.4).

Fig. 13.4 *Periophthalmus koelreuteri*. (Photo courtesy: Damindu Wijewardana)

Table 13.5 Some common species of reptiles, avifauna, and mammal species recorded from different mangrove forests in Sri Lanka

Taxa	Common species
Class Reptilia	Green garden lizard (*Calotes calotes*), common garden (*Calotes versicolor*), common house gecko (*Hemidactylus frenatus*), python (*Python molurus*), mugger crocodile (*Crocodylus palustris*), saltwater crocodile (*Crocodylus porosus*), monitor (*Varanus salvator*), etc
Class Aves	Whiskered tern (*Chlidonias hybrida*), gray heron (*Ardea cinerea*), Indian pond heron (*Ardeola grayii*), great egret (*Casmerodius albus*), intermediate egret (*Mesophoyx intermedia*), little cormorant (*Phalacrocorax niger*), common myna (*Acridotheres tristis*), barn swallow (*Hirundo rustica*), etc
Class Mammalia	Sri Lanka toque monkey (*Macaca sinica*), gray mongoose (*Herpestes edwardsii*), mouse deer (*Moschiola meminna*), wild boar (*Sus scrofa*), fishing cat (*Prionailurus viverrinus*), otter (*Lutra lutra*), jackal (*Canis aureus*), spotted deer (*Axis axis*), etc

Sources: Jayasingham (Jayasingham 2008); Prakash et al. (2017); Priyashantha (2018); Arulnayagam et al. (2021)

13.3.2.2 Amphibians

The common toad *Bufo melanostictus* and the common frog *Limnonectes limnocharis* are the only species of amphibians observed within the mangrove forests, due to the prevailing saline conditions (Arulnayagam et al. 2021).

13.3.2.3 Reptiles

Water snake (*Xenochrophis piscator)*, python (*Python molurus*), cobra (*Naja naja*), crocodile species, and some lizards were observed within mangrove forests (Table 13.5). There were 13 species recorded from different mangrove forests from Rekawa Lagoon, Madu Ganga Estuary, Chilaw and Puttalam lagoons, and

Mundel Lake, located on the northwest coast of the island (Bambaradeniya et al. Bambaradeniya et al. 2002a, b; Arulnayagam et al. 2021).

13.3.2.4 Avifauna

Detailed studies on birds occupying mangroves and related habitats have been conducted in the Negombo Lagoon and nearby Muthurajawela Wetland Sanctuary (Bambaradeniya et al. 2002b), Rekawa Lagoon, Madu Ganga Estuary, Chilaw and Puttalam lagoons, and Mundel Lake, located on the northwest coast of the island (Katupotha 2012). Avifaunal diversity includes a wide range of cormorants, ducks, egrets, gulls, herons, etc. Mangrove wetlands play an important role in attracting migratory birds at any phase of their life cycle, seeking their food in the creeks and channels and nesting in the trees. Arulnayagam et al. (2021) recorded 72 species of avifauna from the different locations of mangroves, and Table 13.5 shows some common avifaunal species in mangrove forests.

13.3.2.5 Mammals

Mammalian fauna are mostly visitors. Many mammals were observed in forests associating with mangrove associates, but only a few species such as bats or rodents were observed in mangroves. In the mangrove forest of Pomparippu Ara-Kala Oya estuaries (in Wilpattu National Park) as well as in those of Menik River (including Katupila Ara and Agara Ara) and Kumbukkan Oya estuaries (in Ruhuna National Park), tracks and dung/scat piles of many mammal species including the elephant (*Elephas maximus*), water buffalo (*Bubalus bubalis*), sambar (*Cervus unicolor*), leopard (*Panthera pardus*), and sloth bear (*Melursus ursinus*) were seen (Table 13.5).

13.4 Ecosystem Services

Mangroves are one of the vital tropical and subtropical coastal ecosystems with a significant amount of the global biodiversity and provide a wide range of ecosystem services that contribute to human well-being (Polanía and Agudelo 2015). Mangroves are the coastal equivalent of tropical forests and hence of important ecological and environmental significance. Sri Lanka is a tropical island with ~1760 km coastline harboring ~1210 km^2 of highly productive lagoon and estuary ecosystems (Harkes 2015). Mangrove areas in Sri Lanka cover less than 0.01% of the land area, due to the very low tidal amplitude the distribution of mangroves is confined to a narrow intertidal belt having a patchy distribution. However, as the coastline runs through different climatic zones and different geomorphological settings, the diversity of mangrove habitats is remarkably high, and hence the species diversity also in mangroves is comparatively high. Mangroves protect Sri Lanka's coastline from sea erosion, while providing diverse livelihoods to the locals. Despite these important services, mangroves are cleared for development activities that have undesirable effects on the well-being of mangrove-dependent communities and the country's economy. Therefore, prior to the implementation of any development activity, it is vital that the biodiversity, ecosystem services, and conservation status of mangroves are assessed.

Deterioration of mangrove vegetation is considered to be one of the main causes for the reduction in fish harvest (Wickramasinghe 1997), and a reduced yield in fisheries may seriously affect the nutrition of local communities. As an example from the Sri Lankan context, an analysis of the data available from the Pambala-Chilaw lagoon complex shows that the fish catch from the lagoon per unit effort has dropped on average from 4 to 1.5 kg between 1994 and 1997 (Wickramasinghe 1997). Similar situations prevail in a majority of the lagoons in Sri Lanka.

The ecosystem services provided by mangroves include riverbank and shoreline stabilization, flood control, groundwater recharge, and pollution control. They also act as breeding and spawning grounds for commercially important marine life such as finfish and crustaceans. In summary, mangrove communities are economically and ecologically valuable and are one of the most productive ecosystems in the world. Coastal communities depend on the interactions and processes that take place within these ecosystems and the valuable services provided by them. Four main types of services are provided by mangroves which can be categorized as follows.

13.4.1 Provisioning Services

These are the direct goods provided by mangrove habitats which can be used for consumption and sale.

13.4.2 Food

Mangroves serve as nursery grounds for many fish and crustacean species, some of which are harvested on a commercial basis. The closely packed pneumatophores and prop roots do not allow larger predators to enter the mangrove environment, providing a safe nursery ground for juveniles, with sufficient food material. Over 40,000 fisher families depend on fishing in estuaries and lagoons containing mangroves, salt marshes, and sea grass beds as a source of income. Mangroves support shrimp farming and traditional fisheries such as brush pile and fish kraals. The highest dependence of local communities on mangrove fisheries has been recorded from Puttalam lagoon, Mi Oya estuary, Chilaw lagoon, and Negombo Lagoon, respectively.

13.4.3 Timber and Fuelwood

Globally, the timber of mangrove flora is used to make furniture, rafters, fences, bridges, poles, boats, and houses. Unlike the mangroves in Southeast Asia, the low standing stock of timber in Sri Lankan mangroves prevent them being used as timber or charcoal on a large scale. In Sri Lanka, mangrove timber is used sparingly for construction, especially for building of temporary housing for the fishing communities near the sea or lagoon. Mangroves are used as firewood in some northwestern coastal areas where no other vegetation exists substantially to be used for this purpose. Light woods are used for mask carving and puppet production. In Negombo Lagoon, wood of *R. mucronata* and *L. racemosa* are used primarily to construct "brush piles," a widely used traditional fishing technique. *R. mucronata* and *L. racemosa* are the most preferred species for the purpose because of their greater durability (due to the presence of tannin) and profuse branching. Mature branches are cut, and the leaves are shed before taking these branches into the predetermined shallow areas of the lagoon and placed close to each other so as to make a square or circular pile of brush in the water. The brush piles mimic mangrove areas, and they provide food and refuge particularly to the juveniles of finfish and shellfish and therefore serve as fish aggregation centers. After a few weeks, depending on the time of the year, brush parks are surrounded with a net, and the mangrove twigs and branches are removed to catch the fish with a scoop net. Brush parks installed in deeper waters are made out of coconut trunks at the margins in order to prevent the twigs being washed away by the moving water. Brush pile fishery in Negombo Lagoon is an incentive for local fishermen to cultivate mangroves, a traditional practice that has been mastered by indigenous communities. Some of the mangrove woodlots that they cultivate particularly in the mudflats of the northern part of the lagoon, near the sea mouth, are maintained with methods that are on par with modern silvicultural practices (Amarasinghe 2009).

13.4.4 Medicines

About 70 different mangrove plant species are listed as having traditional medicinal uses. *Bruguiera*, *Rhizophora*, and *Lumnitzera* are used for the treatment of various ailments and diseases.

13.4.5 Other Non-timber Forest Products

The leaves of many species such as *Nypa* are used for thatching and weaving. The breathing roots of various *Sonneratia* spp. are used to make corks and fish floats. Mangrove plants are also used as sources of sodium, while the ash produced from burning species such as *Avicennia* is used to make soap. The bark of many species produces resins and tannins which are used for curing leather and fish nets. Beach seine fishermen along the western and southern coasts of Sri Lanka use tannin to enhance the durability of their nets. Tannin that is added to dyes used for dying the sails of traditional crafts is obtained from bark collected from mangrove areas of the Puttalam lagoon (Amarasinghe 2009).

13.5 Regulating Services

These are the benefits obtained from the regulation of ecosystem processes such as climate and flood regulation.

13.5.1 Protecting the Shoreline

Mangroves are able to resist the strong forces of wave and wind energy by providing resistance and drag. They are able to absorb between 70% and 90% of the energy of the waves, thereby reducing the strength of waves and currents, resulting in less damage to coastal areas. This protective function is important in shielding coastal communities during natural disasters such as storm surges and cyclones.

13.5.2 Trapping Pollutants

Mangrove roots help to improve the purity of water by filtering out pollutants that reach the sea from inland waters (Amarasinghe 2009).

13.5.3 Supporting Services

These are ecosystem services that are necessary for the production of all other ecosystem services.

13.5.4 Biodiversity

Mangrove ecosystems carry a unique variety of flora and fauna that is not found in any other ecosystem. Organisms occupy habitats associated with the roots, both above and below water level, mangrove soil, stems, bark, leaves, branches, and canopy. The Maduganga estuary in Southwestern Sri Lanka has 303 species of plants and 248 vertebrate species (70 fish, 12 amphibians, 31 reptiles, 124 birds, 24 mammals) (Amarasinghe 2009).

13.5.5 Sequestering Carbon

Carbon sequestration is the process through which plant life removes CO_2 from the atmosphere and stores it as biomass. Therefore, plants are referred to as carbon sinks. Globally, mangroves are important carbon sinks, and measurements suggest that they can capture as much as 1.5 tons of carbon per hectare per year. They also provide more than 10% of essential dissolved organic carbon (i.e., carbon-based nutrients released into the water due to decomposing plant matter) that is supplied to the global oceans from land (Amarasinghe 2009; Perera and Amarasinghe 2018).

13.5.6 Retention/Detention of Sediments

The wide and tangled root system of mangroves is able to trap sediment and prevent it from washing into the sea. This trapping also protects coral reefs from sedimentation. *Avicennia marina* may be the best land stabilizer because of its quick aerial root production and pneumatophores that increase sediment holding capabilities. The roots function to build up sediment, stabilizing the ground and fixing mud banks, thereby preventing erosion. Communities around estuaries and lagoons plant mangroves to protect their land and properties from erosion. In the Negombo Lagoon, a few rows of *R. mucronata* have been planted along the waterfront to form a fence, which protects the land from erosion caused by turbulent estuarine and lagoon waters (Amarasinghe 2009).

13.5.7 Primary Production

Like all green plants, the mangroves manufacture their own food through the process of photosynthesis. Organic matter which is produced by photosynthesis of mangrove plants is the major source of energy available for organisms in coastal waters. It is decomposed by microorganisms into detritus on which most fish, crustaceans, and mollusks are directly dependent on as a source of food. Decaying organic matter from mangroves is broken down into nutrients that are washed into the sea every time the tide goes out. Annually, this amounts to an estimated 12,500 tons of food for marine life (Amarasinghe 2009). This enriches coastal food webs and coastal fishery production.

13.5.8 Aesthetic Services

People obtain nonmaterial benefits from ecosystems through spiritual enrichment, development of learning, recreation, and aesthetic experience. Mangroves provide a recreational habitat for visitors. Mangrove areas on the southwestern coasts – particularly Bentota, Maduganga, and Kaluwamodera estuaries – are used for ecotourism and recreation. Nature observation, recreational fishing, and canoeing are popular leisure activities among tourists. Unfortunately, heavy use of speed boats in the Bentota River has uprooted mangroves in some areas (Amarasinghe 2009).

13.6 Livelihoods

Many mangrove resources are harvested for subsistence purposes (e.g., fuelwood, edible plants, honey, etc.). Local communities settled near mangrove areas are heavily dependent on mangroves for their livelihood. Satyanarayana et al. (2013) highlighted that branches of *Avicennia* spp. are used for brush pile traditional fisheries. Prop roots from mangrove species like *Rhizophora apiculata* are used as fuelwood. Tender leaves of *Avicennia marina* are used as a vegetable (Katupotha 2012). Wood of *Cerbera manghas* is used by Sri Lankans to carve masks and puppets because of its light weight (Miththapala 2008). Moreover, *Nypa fruticans* is used to make alcohol, sugar, and vinegar though in Sri Lanka, it is minimally practiced at present (Ranawana 2017). Tender leaves of *Sonneratia caseolaris* are traditionally used as a curry, and water from the boiled leaves are used as an anti-poison (Bandaranayake 1999). In addition, fruitsof *S. caseolaris* are used to prepare a soft drink (Ranawana 2017). Leaves of *Acrostichum aureum* and *Suaeda maritima* are also used as vegetables (Priyashantha and Taufikurahma 2020). Pneumatophores of *Sonneratia* spp. are porous and used as bottle stoppers and fishing floats (Katupotha 2012).

Fishing is the most important economic activity in the coastal regions of Sri Lanka (Fig. 13.5), and many communities depend upon it for their livelihood as

Fig. 13.5 Fishing is the most important economic activity in the mangrove ecosystem. (Photo courtesy: Sriyani Wickramasinghe and Damindu Wijewardana)

fishery activities provide income for traditional and marginalized groups (Polanía and Agudelo 2015). Fish also constitutes approximately 65% of the animal protein consumption and 13% of the total protein intake for the population of Sri Lanka (Rajasuriya et al. 1995). It is estimated that two-thirds of the world's fishing communities depend on the existence of mangroves (FAO 2003; Rönnbäck 1999). Mangrove areas provide food and shelter for many commercially important aquatic species, and a positive correlation has been observed between near shore coastal shrimp and fish catches and mangrove area cover (Singh et al. 1994; Baran and Hambrey 1998; de Graaf and Xuan 1998; Rönnbäck 1999).

A community survey was conducted in the Northwestern Sri Lanka enlisting all the products collected from the mangrove ecosystem, the amount of each product obtained and if any of these products are sold rather than just used in the household then any selling-buying procedure, the market price of the product and thus the total family value for the products to understand the community livelihoods, the monthly income of each livelihood and the community living pattern in relation to the mangrove ecosystem.

In the northwest of Sri Lanka, mangrove and offshore fisheries are two of the most important livelihood activities associated with mangroves. Most households reported fish, shrimps, crabs, and bivalves (in order of preference) obtained from this mangrove environment, and the fishing activities were observed all along the lagoon. The fish, crabs, shrimps, and edible bivalves were caught using various fishing gears such as fishing lines, dip nets, cast nets, and fishing traps. Travel cost methodology was not able to be used due to the absence of reliable tourism data and information on the number of guests, room rates, and reasons for visit in any of the study sites.

The head of households were interviewed about their use of mangroves as construction material (for making boats or houses, fishing stakes, etc.), fuelwood, as medicinal and edible plants, and about other non-timber forest products (masks, hats, and ornaments). In the case of fuelwood, questions were asked about their preferences for mangrove wood (including for personal use and for sales), in contrast to wood from non-mangrove trees and/or nonwoody resources such as gas and kerosene. The same methods were used to identify the role of mangroves as suppliers of edible plants (with emphasis on its uses, collection, selling practices, and people's preferences), together with reasons for decreased consumption over time (more details are available on https://www.mdpi.com/1424-2818/10/2/20). In summary, in the northwestern area of Sri Lanka, *Bruguiera*, *Rhizophora*, and *Lumnitzera* are used for the treatment of various ailments and diseases; the highest valuation is obtained from aquatic food, including fish, shrimp, crabs, and mollusks (Sarathchandra et al. 2018).

13.7 Threats

More than a third of the world's mangrove forests have disappeared in the last 50 years due to overexploitation and destruction of mangrove habitats. Globally, the rate of mangrove deforestation is between 2% and 8% per year. Some countries have lost more than 80% of their mangrove forest cover over the last 20 years. Shrimp aquaculture accounts for the loss of 20–50% of mangroves worldwide. It is predicted that developing countries will lose 25% of their remaining mangrove cover by 2050 (Amarasinghe 2009).

Mangroves are the coastal equivalent of tropical forests and hence of important ecological and environmental significance. In Sri Lanka, as in many other countries, conversion of mangrove forests to other uses has resulted in a considerable decline of these ecosystems (Legg and Jewell 1995). Despite their multiple values, mangroves are disappearing at an alarming rate. Less than half the original extent of mangroves remains in the world today, and the rate of loss is highest in the Indo-Malayan region which also has the highest mangrove diversity in the world. In Sri Lanka, with the increasing population in coastal areas, the demand for land has risen. Because of this, there is pressure to use intertidal coastal wetlands for development activities. As a result, the mangroves are among the world's most threatened ecosystems. Some major threats faced by mangroves in Sri Lanka include as follows.

13.7.1 Overexploitation of Mangrove Products

Most of the mangrove habitats are degraded because of overexploitation for fuel-wood and timber. In Puttalam lagoon, mangroves are overused heavily particularly for firewood and tannin (Fig. 13.6b).

Fig. 13.6 Discharge wastewater to the mangrove forest (**a**) and cutting mangroves for domestic use (**b**) (Photo courtesy: Damindu Wijewardana)

13.7.2 Habitat Destruction

Coastal development, land conversion for aquaculture, salt pond (saltern) construction, and agriculture contribute to degradation of mangrove habitats. Mangrove areas are cleared for highway construction, hotel construction, and human settlements. This has resulted in altered hydrology at Mi Oya estuary, loss of prawn species in Chilaw lagoon, and a decline in fishery resources in Mundel Lake. Mangroves are affected seriously by inland freshwater diversion schemes for irrigation. It is estimated that 11% of mangrove habitats are degraded globally because of inland water extraction. In areas such as the Kalametiya Lagoon, diverse mangrove stands have been replaced by monospecific *Sonneratia caseolaris* stands due to the release of excess freshwater into the lagoon.

One of the major factors that have led to their destruction in Sri Lanka is shrimp farming. Valiela et al. (2001) reported that the conversion of mangroves to aquaculture ponds is responsible for about 38% of the total mangrove loss that has occurred in the country. In addition to the direct destruction of mangroves, shrimp farming has also caused the degradation of water quality in lagoons and the loss of biodiversity in the remaining patches of vegetation (De Silva and de Silva 2002; Wolanski 2000). Local political patronage is one of the main causes for this adverse situation despite Sri Lanka being the first tropical country with a centrally managed integrated coastal zone management program (Clark 1996).

In Sri Lanka, shrimp farming did not start until the mid-1980s in the western coastal belt between Kalpitiya and Negombo, but there has been a rapid expansion in shrimp cultivation in recent years (Jayasinghe and De Silva 1993). In 1996, Sri Lanka produced 4000 metric tons of shrimp (*Penaeus monodon* Fabricius) at a value of US$ 540,000 (FAO 1998), and during the period 1985–1992, it contributed between 53% and 73% of the total foreign exchange earnings from the fishery sector (Jayasinghe and Macintoch 1993). As recently as 1997, the director of the Aquaculture Development Division, Ministry of Fisheries and Aquatic Resources in Sri Lanka stated that more areas were to be brought under shrimp farming (Jayasekara 1997).

The mangrove areas of Sri Lanka have been reduced and impoverished in quality under an increasing human pressure (Silva and Balasubramaniam 1984, Balasubramaniam 1985; Jayewardene 1986). In recent years, shrimp farming has emerged as a major threat to mangrove ecosystems in Sri Lanka (Jayasinghe and De Silva 1993). Conversion of such ecosystem to alternate development activities deprives all the beneficial uses of mangrove ecosystems and thus would adversely affect the well-being of mangrove-dependent communities, country's economy, and social welfare. In order to make sound judgments of development activities, it is vital that the uses and values of mangroves to local communities are identified and estimated.

Despite these beneficial uses of mangrove ecosystems, the vast amount of mangrove habitat has been destructed for commercial purposes specially converting to prawn farms. It was estimated that around 3385 ha of mangrove cover along the shores of Puttalam lagoon, Dutch Bay, and Portugal bay complex. A wide destruction has taken place from 1981 to 1992 leaving around 993 ha of mangrove cover in the Puttalam lagoon (Amarasinghe and Perera 1995).

13.7.3 Pollution

Inland farming, housing, and development result in chemical and sewage pollution (Fig. 13.6a), which can overfertilize coastal waters, causing the growth of "tides" of algae which can turn toxic and rapidly reduce productivity by blocking sunlight from reaching below the water surface (Amarasinghe 2009).

13.7.4 Invasive Alien Species (IAS)

IAS does not remain confined to the area into which they were introduced; they become established in natural ecosystems and threaten native species. IAS poses a threat to the provisioning services of mangroves. In Southwestern Sri Lanka, the mangroves are being affected by the spread of pond apple (*Annona glabra*) (Amarasinghe 2009).

13.7.5 Climate Change and Global Warming

In recent decades, global warming and climate change have become prominent threats. Changes in temperature, CO_2 levels, rainfall patterns, and increases in frequency of storms and hurricanes have been observed. Both global warming and climate change are directly linked to anthropogenic activities. Changes in precipitation as a result of climate change will affect growth, productivity, and seedling survival of mangroves. Decreased precipitation and increased salinity and salt water intrusion caused by the rise in sea levels could favor more salt-tolerant species and change species composition. Increased natural disasters will increase physical damage to mangroves.

Sea level rise will result in the loss of land occupied by mangroves. Changing wave climates increase coastal erosion and damage mangrove habitats. Climate change, in short, will have serious impacts on mangroves, which will, in turn, affect their ecosystem services (Amarasinghe 2009).

The climate of Sri Lanka has been fluctuating at an alarming rate during the recent past. These changes are reported to have significant impacts on the livelihoods of the people in the country. The mangrove ecosystem is especially vulnerable to the impacts from climate change because it is already depleting at an alarming rate due to anthropogenic activities (Khaniya et al. 2021) and inhabiting in the intertidal zone, thus more likely to be early indicators of the impact from climate change such as sea level rises (McLeod and Salm 2006; Nitto et al. 2014). Currently, relative sea level rises have been a lesser threat to mangroves when compared to non-climate-related anthropogenic stressors. However, more empirical studies should be conducted to understand the mangrove responses to sea level rises in Sri Lanka. For instance, more studies on the ability of the mangrove forest to migrate to more landward zones, salinity tolerance, seed dispersal, etc. are essential.

Mangrove species composition can strongly affect a mangrove's resilience and resistance to sea level rises. The accurate species composition in Sri Lanka is still uncertain, and the mangrove species present at each mangrove patch also need to be well assessed in a scientific manner in order to support future conservation efforts (Prasanna et al. 2017). Further, restoration practitioners and local authorities should keep pace with the scale changes predicted under most climate change scenarios (Huxham et al. 2010).

13.8 Regeneration of Mangroves/Silviculture

In general, mangroves regenerate naturally when they are in suitable conditions for their dispersal, germination, growth, and establishment. However, due to changes in geomorphological and hydrological conditions caused by anthropogenic activities or natural disasters, the natural regeneration of mangroves is hampered. For example, in 2004, Sri Lankan mangroves were severely damaged by the tsunami in the Indian Ocean; 1200 km of coastline was affected. As a consequence, the natural habitat of the mangroves altered and did not recover well. After 2004, Sri Lanka received international attention for mangrove restoration projects and a significant amount of funding (Kodikara et al. 2017) to aid these projects conducted by many governmental and nongovernmental organizations.

According to a study done by Kodikara et al. (2017), approximately 1000–1200 ha of mangroves have been planted in 23 sites in Sri Lanka, and 20 of them were established after the tsunami catastrophe (2004) (Fig. 13.7). Unfortunately, the study revealed that the current extent of the surviving planted area is only about 200–220 ha, only a 20% success rate. Furthermore, a total of 67 planting attempts were done during a period of 8 years, and 36 of them showed zero survival. Many restoration attempts were unsuccessful in tsunami-affected areas, while the majority of successful restoration sites were in areas unaffected by the tsunami (Kodikara et al. 2017). These restoration failures happen mainly due to lack of awareness or ignorance of the major ecological components of mangrove restoration sites such as hydrology, salinity, and species composition of each habitat. Additionally, involvement of untrained people with lack of expertise in mangrove restoration could worsen these restoration attempts. To overcome these problems, involvement of experts who have experience on mangrove restoration is essential (Elster 2000;

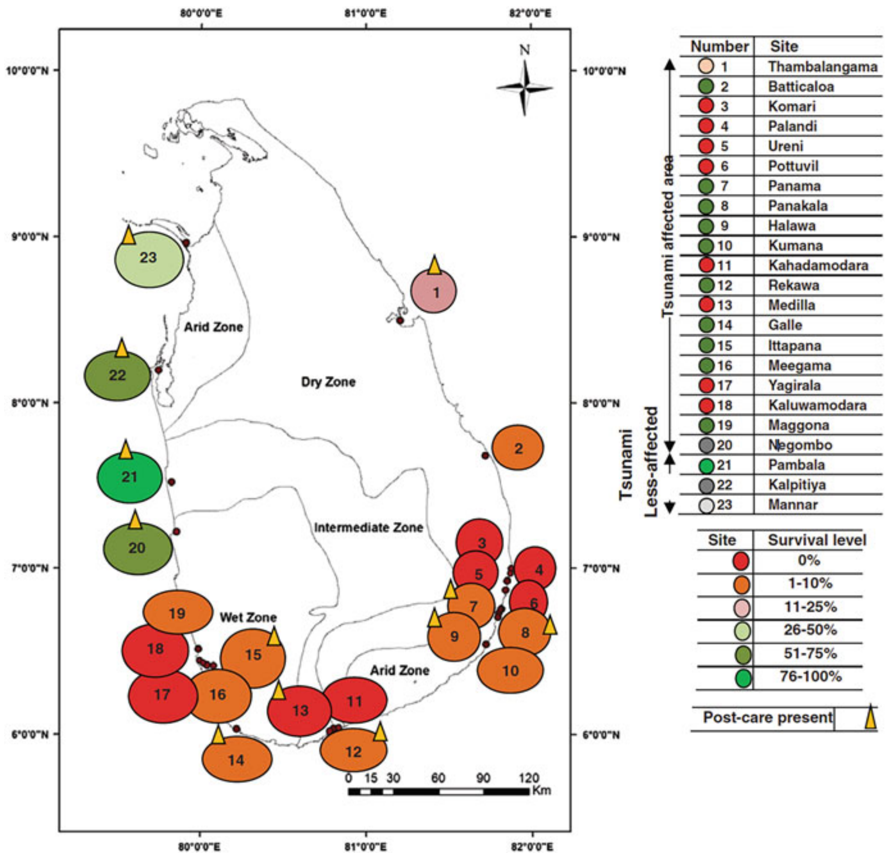

Fig. 13.7 Map showing the restoration project sites along the Sri Lankan coastline with respect to major climate zones. Black circles show the actual locations of restoration project sites. Different colors represent the level of success, and a yellow triangle shows the status of post-care in each site (Source: Kodikara et al. 2017)

Primavera and Esteban 2008; Ahmad 2012). Scientific understanding of the mangrove ecosystem is crucial together with some preliminary research on the particular restoration site. Additionally, proper post development activities should be scrutinized closely by collective efforts from all the pertinent authorities.

Germination behavior is one of the important characters that restoration practitioners should consider prior to restoration efforts. Interestingly, a wide range of germination behavior can be seen in mangrove plants. According to the germination behavior, mangrove species can be classified into two groups, viviparous and non-viviparous species. In viviparous species, germination and subsequent development of the propagule take place while the fruit is still attached to the mother plant (Tomlinson 1994), whereas in non-viviparous species, germination and subsequent development of the seeds/diaspore take place after seed dispersal (Tomlinson 1994; Baskin and Baskin 2014). There are seven true viviparous and four crypto-viviparous mangroves in Sri Lanka (Table 13.3).

The majority of mangrove regeneration efforts in Sri Lanka have been conducted by planting viviparous species such as *Rhizophora* spp. and *Bruguiera* spp., with the use of non-viviparous species (Fig. 13.4) for restoration projects used to a lesser extent (Kodikara et al. 2017). This happens due to many reasons, that is, direct seedling/propagule planting method is more feasible, propagules are easy to find from the wild in large amounts, maintenance in the nurseries is easy, and there is a lack of deep dormancies.

Knowledge on seed germination behavior (dormancy, dormancy-breaking requirements, and germination requirements) is crucial for meaningful conservation efforts of mangroves (Duke et al. 2007; Polidoro et al. 2010; Van Lavieren et al. 2012). Instead of collecting seedlings from the field, seedlings can be raised in nurseries for large-scale restoration activities. However, one of the major constraints faced in practicing this method is the lack of knowledge on seed germination behavior of most of the true mangrove and mangrove-associated species (Field 1998; Ellison 2000; Baskin and Baskin 2014). Seed germination and dormancy studies have been mainly conducted on viviparous mangrove species, while only a few studies have been reported on other mangrove and mangrove-associated species in Sri Lanka (Baskin and Baskin 2014). These seed dormancy studies are important to compare the relative importance of seed dormancy classes in mangrove plants (Baskin and Baskin 2014) and elucidate the dynamics of ecosystems (Skoglund 1992) and crucially in crafting strategies for conservation efforts.

De Silva and Amarasinghe (2021) mentioned that natural regeneration could be observed in some abandoned shrimp ponds around Chilaw lagoon area where there is less salinity relative to other abandoned ponds in other areas. They also mentioned that rehabilitation of abandoned ponds with high salinity has not been attempted yet and to do that, high salt-tolerant plants should be considered to improve the health of the degraded soil. Therefore, more research should be done in order to identify the mangrove species that can be germinated and established under high salt conditions.

Some studies have been conducted in Sri Lanka on the effect of salinity on mangrove seed germination, seedling, and establishment (Wijayasinghe et al. 2019; De Silva and Amarasinghe 2021; Kodikara et al. 2017). De Silva and Amarasinghe (2021) investigated the potential of using mangrove species for rehabilitation of high saline environments by revealing the capacities of species to remove salt from sediment with four viviparous species, namely, *Rhizophora apiculata*, *R. mucronata*, *Ceriops tagal*, and *Avicennia marina*, and they showed that the highest salt tolerance is in *A. marina* and the lowest is in *R. apiculata*. Therefore, *A. marina* appears to be the most suitable mangrove species not only for coastal mangrove restoration but also for rehabilitating salinity-affected landscapes. Kodikara et al. (2017) also studied the growth and survival of *R. apiculata*, *R. mucronata*, *A. marina*, *A. officinalis*, *Bruguiera gymnorrhiza*, and *B. sexangula* seedlings under three contrasting salinity treatments over a 30-week period, and they revealed that the low salinity treatment provided the best conditions for initial establishment and growth of the seedlings of all species until 15–20 weeks of age. However, the same seedlings showed better performance under moderate salinity after 15–20 weeks of age. This information is critical for species selection for restoration and adjusts the conditions when managing a nursery for restoration. However, more studies should be done in order to help restoration efforts be more successful.

13.9 Conservation

The Sri Lankan government has taken many steps in order to protect the valuable mangrove ecosystem including implementing legislations. Sri Lanka claims to be the first nation in the world to protect all its mangroves, making it illegal to cut them down anywhere in the island, and the first to open a mangrove museum (in Pambala, Chilaw). Sri Lanka was also named as a leader for conservation of mangroves in Commonwealth countries (Priyashantha and Taufikurahma 2020).

As the increasing demand for fish protein in the island and for the export market is leading to the overexploitation of fishery resources, it is a timely concern to develop sustainable fishery and aquaculture practices (Jalaldeen and Vinobaba 2010), which will eventually be an alternative to the depletion of a fishery resource and thus amend environmental pressure by becoming a stable source of income for Sri Lankan coastal people. Fishery resources are an asset to Sri Lanka; if managed efficiently and sustainably, it can be a major part of foreign export income. Therefore, it is essential to impose legal barriers prohibiting the use of illegal devices such as nets with a small mesh size that capture immature stages and spawning stages. However, if the people involved are not properly concerned on these issues, legal barriers will not serve any purpose, and ultimately if the lagoon and coastal fishery fail, fishermen will be the ones most affected. Therefore, awareness and education through mass media and extension services will do a great service to safeguard this invaluable resource in Sri Lanka.

Community surveys exploring suggestions from local people for the conservation of the mangrove ecosystems around them have received the following feedback:

- Implement policies and regulations on shrimp farming fairly.
- Provide job opportunities for skilled workers.
- Improve sanitation facilities.
- Introduce proper housing scheme systems.
- Pose strict fines for those who neglect rules and regulations.
- Remove barriers for marine fisheries.
- Construct a proper fishing port.
- Minimize political interventions in shrimp farming.

- Introduce alternative livelihoods.
- Build community-based ecological mangrove rehabilitation.
- Continue conducting more awareness programs but with solutions for the existing conflicts, not just information and what is happening.

Many coastal inhabitants do not understand the true economic value of the ecosystem forgone by destroying it though they have experience on depleting fishery products for the past few years. They are willing to contribute to any programs which will sustain both their livelihoods and ecosystem protection together. Continuing the assessment of the ecosystem status will help in conserving threatened ecosystems and informing government policy makers at what level and how political interventions should be involved, such as effective monitoring of mangrove ecosystems, arrangement of marketing facilities, and professional training on fish catch processing techniques.

Mangroves are great resources which need to be preserved; when dealing with coastal development in the phase of global climate change where rising sea levels are recorded, healthy mangrove forests are the best protectors of the coastline. Losing those means increasing the chances for coastal subsidence, erosion, and storm damage which will come with its own repairing cost. Therefore, mangrove swamps should not be seen as useless areas of vegetation to be cut down indiscriminately for aquaculture, agriculture, housing, and industrial development but as viable resources to be developed in a sustainable manner.

A positive recent development in mangrove conservation in Sri Lanka is that the government agreed to give legal protection to the remaining mangroves of the whole island totaling to a ~8800 ha and to reestablish another 3900 ha of mangroves (Huxham 2015) which hopefully will not be limited to papers and be practically implemented. In 2001, MOFE (Ministry of Finance and Economy), by way of Circular No 2001/5, empowered the Forest Department to manage all the mangrove resources in the country and take necessary action for their protection and development (IUCN 2001). Fourteen mangrove areas, in all, were surveyed and their boundaries demarcated and were declared as conservation forests in 2002 (IUCN 2011). Currently, the ministry of environment has drafted national guidelines, formats, and information for restoration of mangrove ecosystems and propagation of mangroves (MoMD & E 2019).

However, still, not enough attention has been paid to conserve the very rare and endangered mangrove species, and further steps have not been taken even to educate the locals about those species. In addition, any continuous observations or assessments have not been carried out on the conserved mangrove forests (Jayatissa et al. 2002).

13.10 Highlights of the Sri Lankan Mangrove Conservation Project

Highlights of the Sri Lankan Mangrove Conservation Project
Seacology, in collaboration with Sri Lanka-based NGO Sudeesa, is working to make Sri Lanka the world's first nation to protect all of its mangrove forests. The project has managed to replant over 1,200 acres of mangroves, and almost a million mangrove seedlings have been raised in new nurseries—double the project's goal. Business training programs have been conducted for more than 14,000 people, and almost 12,000 of them received microloans to start or improve their businesses. Small groups of women called the Community Beneficiary Organizations (CBOs) have been established in order to manage the process smoothly. Women in the community of Iranawila village, in Puttalam District, have been given three-day training sessions. One project participant opened a retail shop with Rs 10,000 microloan obtained from the microfinance components of the program. They now earn revenue of about Rs 1500 per day with a daily profit of about Rs 150. She is planning to get a second loan after repayment of the first to improve her business further. Another person initiated a tailoring business, which increased the family's income, while another started production of snacks with an Rs 10, 000 microloans.

Seacology Sudeesa established the Sri Lanka Mangrove Museum at Pambala North adjacent to the Chilaw lagoon. This, the key component of Sri Lanka Mangrove Conservation Project, was opened on July 26, 2016. The main objective is to educate locals and visiting eco tourists alike about the ecological and economic importance of mangroves and introduce thousands of guests to conservation and restoration of mangrove ecosystems in Sri Lanka.

The project has received substantial international recognition. The United Nations gave Seacology a UNFCCC Momentum for the Change Lighthouse Activity Award, recognizing the project's work to fight climate change. Further, Sudeesa received the 2019 Presidential Environment Award, presented by former Sri Lankan President, Mr. Maithripala Sirisena (https://www.seacology.org/project/sri-lanka-mangrove-conservation-project/).

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Chapter 14
Mangroves in Myanmar

Toe Toe Aung

Abstract The mangrove extent in Myanmar, according to the most recent forest resources assessment in 2020, has been estimated as 1.12 million acres. Among three main tracts of mangroves—Rakhine coastline, Ayeyarwady delta, and Tanintharyi coastline—the mangroves in the Tanintharyi coastline have now turned into the largest areal extent despite the fact that the Ayeyarwady delta had the largest in the past. With a large share of the Bay of Bengal Large Marine Ecosystem, coastal and delta ecosystems including mangroves, coral reefs, seagrass beds, beaches, and dunes largely flourish throughout the Myanmar coastline. In this context, the Tanintharyi coast showed the highest species diversity of mangrove flora while the least species diversity was observed in the Ayeyarwady delta. Provided that a total of ten prominent provisioning, regulating, supporting, and cultural services were considered, fishery nursery and habitat has shown its highest value in the mangrove ecosystem services, followed by coastal protection. In particular for the latter services of coastal protection, local communities and their tremendous properties were saved, and lifelong lessons were learned during the deadliest impacts of Cyclone Nargis 2008. The mangrove ecosystems in Myanmar, however, have been alarmingly threatened due to overexploitation of fuelwood and charcoal production; mangrove conversion to other land uses such as rice fields, shrimp farming, and salt pans; coastal and delta development with human settlement; improper revenue collection on mangrove products in forest management; and climate change and natural disasters. One of the major measures to tackle the existing issues and problems is community-based forest management, called "community forestry (CF)" in mangroves that is a remarkable initiative since 1995 in the aspects of partnership, participation, and decentralization in managing the mangroves in Myanmar. In connection with the findings on the CF study regarding the regeneration of some resilient mangrove species after the impact of Cyclone Nargis, coppice management would be supportive and beneficial to local communities in their own mangrove management. The case study in the chapter demonstrated as well that most of the local stakeholders had fairly sufficient awareness and attitudes to enable

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active participation in mangrove restoration although there were slight differences between the different stakeholders. In particular, poorer attitudes were observed in some migrant communities compared to the settled communities. In developing a mangrove management strategy, inclusiveness should, therefore, be one of the key take-home messages by prioritizing the subsistence needs of the local people plus economic benefits.

Keywords Mangroves · Myanmar · Ecosystem services · Coastal communities · Cyclone Nargis · Awareness and attitude · Inclusiveness

14.1 Physical Attributes and Characteristics

14.1.1 Mangrove Coverage

The World Atlas of Mangroves (Spalding et al. 2010) shows that mangroves cover most parts of Myanmar's coastlines with an estimated area of 502,900 ha, representing 3.3% of the global total and making Myanmar the third largest mangrove coverage in Asia, after Indonesia and Malaysia. In the past, the majority of mangroves occurred in the Ayeyarwady delta, with the remainder in Tanintharyi and a lesser portion in the Rakhine area. Currently, however, mangroves in the Ayeyarwady delta are being depleted at an alarming rate; almost 72% of mangroves in the delta have already disappeared (Table 14.1). With the severe degradation in the mangroves of the Ayeyarwady delta, the mangroves in the Tanintharyi have now turned into the largest areal extent. Similar trends of alarming mangrove degradation and depletion have been shown by the NASA assessment and predictions as shown in Table 14.2. NASA estimated that only 641,486 acres of mangroves will be left in Myanmar by 2030, and the worst condition will fall into the Ayeyarwady delta in which only approximately 32,124 acres of mangroves are estimated.

In Myanmar, the administration of such mangrove forests is with a district-level base. In terms of district forest management, there are 13 districts that represent the existence of mangroves along the coasts, dense or sparse. Considering from the north to the south, for the conservation and management of mangroves together with other

Table 14.1 Mangrove cover change from 1990 to 2015

No.	Region/state	1980 (acres)	2015 (acres)	2020 (acres)	Coverage (%)	Remaining from 1980 to 2020 (%)
1.	Rakhine State	415,137	313,792	302,933	27	73
2.	Ayeyarwady Region	679,540	194,925	192,726	17	28
3.	Tanintharyi Region	647,416	635,266	623,625	56	96
Total		1,742,093	1,143,983	1,119,284	100	64

Sources: FAO (2014, 2020), FD (2019b)

Table 14.2 Mangrove cover assessment in Myanmar

No.	Region/state	Area (acres)		
		2000	2013	2030
1.	Ayeyarwady Region	202,132	114,163	32,124
2.	Rakhine State	428,481	363,245	170,009
3.	Tanintharyi Region	512,744	504,095	439,353
Total		1,143,357	981,503	641,486

Sources: Weber et al. (2014)

marine resources, Rakhine State is composed of five districts, Ayeyarwady Region three districts, Yangon Region one district, Mon State one district, and Tanintharyi Region three districts. Out of the three districts in the Ayeyarwady Region, Pyapon district manages the largest part of mangroves in the Ayeyarwady delta. These 13 districts have their corresponding management plans to manage forests including mangroves. In the British colonial days, the Ayeyarwady delta was exclusive for the conservation and management of mangrove forests and managed with the Delta Working Plan intended for fulfilling the basic needs of fuelwoods for local communities.

14.1.2 Tides and Their Effects

The tides and their effects are important characteristics in implementing mangrove operations (Hoe 1952). It is a well-known fact that in the Delta, tides rise and fall twice in every 24 h and that each rise or fall occurs about 48 min later each day. The Myanmar calendar which follows the lunar month is useful to indicate the behavior of tides. There are a number of compositions and rhymes in Myanmar illustrating the following certain points:

1. On waxing days, the tide rises at moonset.
2. On waning days, the tide rises at moonrise.

In these two rhymes, the terms moonset and moonrise are used because the setting and the rising can be seen better and cannot be mistaken.

1. On the seventh waning day, the moon rises at midnight.
2. On the 13th day (waxing or waning), the tide rises at sunset or at daybreak.

For fishermen, the latter rhyme is supplemented by catching shrimp and fish at 6 o'clock (with the morning tide). The time at which the tide rises or falls at a place in the delta depends on its distance from the sea and occurs later as the distance increases. At the northern end of deltaic reserves, Table 14.3 gives the approximate times of rises. Tides are very important to mangrove managers and practitioners as well as to every inhabitant, in particular fishermen and the fishery production sector to the delta. Tides largely determine soil formation and hence the rate and kind of

Table 14.3 Tide table according to the dates of Myanmar lunar calendar

No	Day, waxing or waning	Time of rise A.M/P.M		Nature of tides	Myanmar term
		Hour	Minute		
1	First	7	12	High rise	Yehta
2	Second	8	0	High rise	Yehta
3	Third	8	48	High rise, spring tide	Gaungye
4	Fourth	9	36	Almost as high as gaungye	Yesahmi
5	Fifth	10	24	The beginning of the low rises, i.e., medium rise (lower each day)	Yethe-u
6	Sixth	11	12	The beginning of the low rises	Yethu-u
7	Seventh	12	0	The beginning of the low rises	Yethe-u
8	Eighth	12	48	Low rise	Yethe
9	Ninth	1	36	Low rise	Yethe
10	Tenth	2	24	Lowest rises, neap tide	Yesinsin-the
11	Eleventh	3	12	Small rise	Yenuhta
12	Twelfth	4	0	Small rise	Yenuhta
13	Thirteenth	4	48	Small rise	Yenuhta
14	Fourteenth	5	36	The beginning of the low rises, i.e., medium rise (higher each day)	Yehta-u
15	Fifteenth	6	24	The beginning of the low rises, i.e., medium rise (higher each day)	Yehta-u

growth and carry seagrass and mangrove tree seeds to the sea and to accretions which are thereby afforested.

14.2 Ecology and Ecological Processes

With a large share of the Bay of Bengal Large Marine Ecosystem, Myanmar shares common maritime boundaries with Bangladesh, India, and Thailand. The continental shelf covers approximately 230,000 km^2 with a relatively wider portion in the central and southern regions (MFF 2016). The Exclusive Economic Zone (EEZ) is about 486,000 km^2 (BOBLME 2012). Over such a long coastline of over 2800 km from north to south, the Rakhine coast, Ayeyarwady delta, and Tanintharyi coast are the three prominent ecological coastal zones of Myanmar (Fig. 14.1). Mangroves, coral reefs, and seagrass beds flourish mainly in the Myeik Archipelago. Estuaries and mudflats are common in the Ayeyarwady delta, while beach and dunes occur throughout the Myanmar coastline. The diversity of mangroves species found, therefore, are high, and the species distributions and compositions of mangroves differ among the three coastal regions.

Coral reefs and seagrass beds are key ecosystems associated with mangroves. These associated marine ecosystems of Myanmar remain largely unexplored, and the

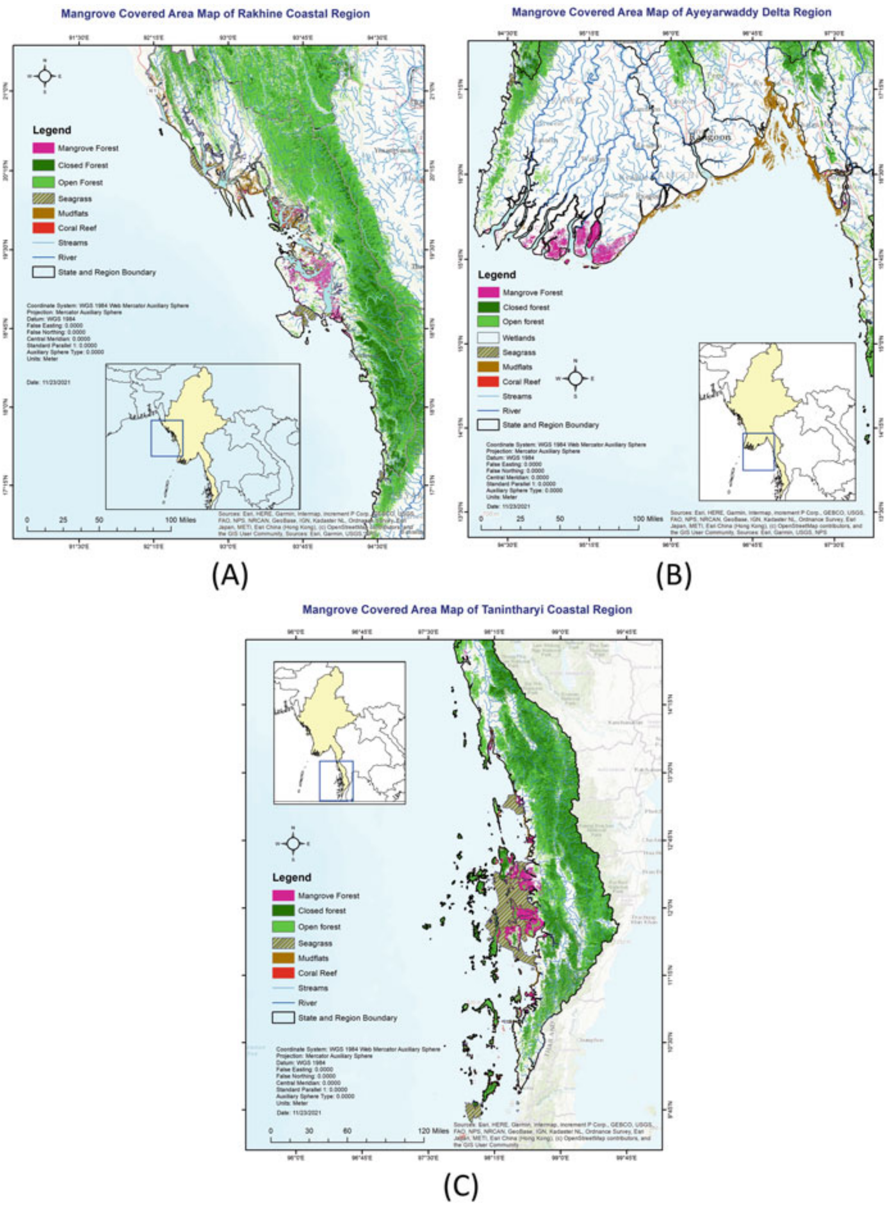

Fig. 14.1 Three main coastlines in Myanmar depicting mangrove area: (**a**) Rakhine coast, upper; (**b**) Ayeyarwady delta, central; and (**c**) Tanintharyi coast, lower

species diversity and health of these two ecosystems are poorly known. An extrapolation of potential habitat area of coral reefs is suggested to be 187,000 ha (BOBLME 2012). Seagrass beds are found in shallow areas interacting with both mangrove and reef communities. There is little information on the status and distribution of seagrass in Myanmar, and the data show that ten seagrass species are currently identified in Myanmar waters (Novak 2009; Tint Tun and Bendell 2010). The health of these key coastal ecosystems largely depends on its nearby mangrove ecosystem and vice versa.

14.3 Floral Biodiversity

The floral patterns of mangroves in the Rakhine coast and the Ayeyarwady delta are very similar to those of the Sundarbans mangrove in Bangladesh and India because of the widespread existence of the genus *Heritiera*. The species diversity in the Myeik Archipelagos of the Tanintharyi coast are more closely related to those in the Ranong region of Thailand. According to the *Mangrove Guidebook for Southeast Asia* by Giesen et al. (2006), there are 148 mangrove plant species in Myanmar; 34 are true mangrove species and the others are shrubs, herbs, and climbers, and associate mangroves. In general, the genus *Rhizophora*, *Sonneratia*, *Avicennia*, *Bruguiera*, *Ceriops*, and *Xylocarpus* spp are dominant in Myanmar (Zöckler and Aung 2019; Nay 2002). The number of mangrove floral biodiversity over all the coasts is not stable as it largely depends on the different sources, and no comprehensive and scientific research has been carried out to cover the whole coastline. The data are produced from quick remote assessment, desk reviews, and the collection of site-specific studies and findings.

In the Ayeyarwady delta, 29 species of mangrove trees are stated, forming the most complicated mangrove system in Asia (Nay 2002). In particular, *Heritiera fomes* is widespread and dominant, and other species that exist this delta include *Excoecaria agallocha*, *Bruguiera gymnorrhiza*, *Cynometra ramiflora*, *Ceriops decandra*, and *Avicennia officinalis* (Ono 2007).

The community patterns of mangrove species after high disturbance by human-induced factors as well as natural disasters have proved to have changed the composition of species (Aung et al. 2013). Long-term observation for 5 years after the impacts of Cyclone Nargis showed that the trends for the mangrove communities of *Avicennia officinalis*, *Bruguiera sexangula*, and *Sonneratia caseolaris* revealed increases in their recovery pathways, while those for *Heritiera fomes* and *Rhizophora apiculata* illustrated decline in their populations. The most prominent finding was that *R. apiculata* communities had disappeared and replaced with *A. officinalis* communities. It is therefore concluded that in case of the same intensity of cyclone like Cyclone Nargis occurs once every decade in the future, *A. officinalis* and *S. caseolaris* species show increasing trends so that they can be supposed to be more persistent and become dominant in the delta compared with other species. Accordingly, they are likely to replace other sensitive communities, in particular

R. apiculata. In terms of wind damage, the sensitivity of species in the Rhizophoraceae and the resilience of those in the Avicenniaceae have also been noted in Australian mangroves that were subjected to cyclones (Woodroffe and Grime 1999). It is also claimed (Smith and Duke 1987) that there are very few Rhizophoraceae in the Sundarbans and that this may be because the adjacent Bay of Bengal receives 30–40 typhoons a year.

Similar to the dominance of specific mangrove species communities after wind-induced disturbance, the most common species grown for plantations since mangrove rehabilitation started in 1982 by the Forest Department (FD) are *Avicennia officinalis*, *A. marina*, *Sonneratia caseolaris*, and *Bruguiera* species. In current mangrove rehabilitation projects, the two most common species planted are *A. officinalis* and *S. caseolaris* as these are fast growing and provide protection against cyclones and natural disasters with the quick returns of coastal protection services.

The mangrove species and communities are therefore observed being unstable in the Ayeyarwady delta due to the compounded effect of natural and human-induced disturbance. Regardless of the community shift and species disappearance, the 40 true mangrove species with their conservation status in Myanmar are listed in Table 14.4 (Giesen et al. 2006; Aung 2016; Yong 2016), but more comprehensive study and scientific research are needed.

San (2020) stated that among all three main mangrove tracts in Myanmar, the coastal study site of the Tanintharyi coast showed the highest species diversity of mangrove vegetation while the least species diversity was observed at the coastal site of the central region where the ground level was higher and species zonation was mostly dominated by the high intertidal species community. Roth et al. (1994) also noted that the greater the disturbance, the lower the species richness and evenness, with the increasing dominance of fewer species. The indices for the species diversity and evenness of the studies over all three coastlines in Myanmar are shown in Table 14.5.

14.4 Faunal Biodiversity

The mangroves in Myanmar are supporting a wide range of vertebrate and invertebrate species, including several globally threatened mammal and bird species. For example, the fishing cat *Prionailurus viverrinus* (EN) (Fig. 14.2) and smooth-coated otters *Lutrogale perspicillata* (VU) have been regularly observed in the Tanintharyi Region (Zöckler and Aung 2019). Furthermore, the Asian wild dog called dhole *Cuon alpinus* (VU) has been recorded in the delta region (Zöckler and Kottelat 2017). Quite prominent and possibly unique for Myanmar and its coastal habitats is the good number of Irrawaddy dolphins *Orcaella brevirostris* frequently entering the mangrove channels and coasts near the mangroves in all three mangrove regions (Zöckler and Aung 2019). The globally near-threatened (NT) Indo-Pacific humpbacked dolphin, *Sousa chinensis*, is still present in good numbers (Moses and

Table 14.4 True mangrove species and their conservation status in Myanmar

No.	Species name	Family	Ayeyarwady delta	Rakhine/western coastline	Tanintharyi/southern coastline	Conservation status
1.	*Acanthus ebracteatus*	Acanthaceae	☑	☑	☑	LC
2.	*Acanthus ilicifolius*	Acanthaceae	☑	☑	☑	LC
3.	*Acanthus volubilis*	Acanthaceae	☑	☑	☑	LC
4.	*Acrostichum aureum*	Pteridaceae	☑	☑	☑	LC
5.	*Acrostichum speciosum*	Pteridaceae	☑	☑	☑	LC
6.	*Aegialitis rotundifolia*	Myrsinaceae	☑	☑	☑	LC
7.	*Aegiceras corniculatum*	Plumbaginaceae	☑	☑	☑	NT
8.	*Aglaia cucullata*	Meliaceae	☑	–	–	DD
9.	*Avicennia alba*	Avicenniaceae	☑	☑	☑	LC
10.	*Avicennia marina*	Avicenniaceae	☑	☑	☑	LC
11.	*Avicennia officinalis*	Avicenniaceae	☑	☑	☑	LC
12.	*Brownlowia tersa*	Tiliaceae	☑	–	☑	LC
13.	*Bruguiera cylindrica*	Rhizophoraceae	☑	☑	☑	LC
14.	*Bruguiera gymnorrhiza*	Rhizophoraceae	☑	☑	☑	LC
15.	*Bruguiera hainesii*	Rhizophoraceae	☑	☑	☑	CR
16.	*Bruguiera parviflora*	Rhizophoraceae	☑	☑	☑	LC
17.	*Bruguiera sexangula*	Rhizophoraceae	☑	☑	☑	DD
18.	*Ceriops decandra*	Rhizophoraceae	☑	☑	☑	NT
19.	*Ceriops tagal*	Rhizophoraceae	☑	☑	☑	LC
20.	*Cynometra iripa*	Fabaceae	☑	☑	☑	LC
21.	*Dolichandrone spathacea*	Bignoniaceae	☑	☑	☑	LC
22.	*Excoecaria agallocha*	Euphorbiaceae	☑	☑	☑	LC
23.	*Heritiera fomes*	Sterculiaceae	☑	☑	☑	NT
24.	*Heritiera littoralis*	Sterculiaceae	☑	☑	☑	LC
25.	*Kandelia candel*	Rhizophoraceae	☑	☑	☑	LC

26.	*Lumnitzera littorea*	Combretaceae	☑	☑	☑	LC
27.	*Lumnitzera racemosa*	Combretaceae	☑	☑	☑	LC
28.	*Nypa fruticans*	Arecaceae	☑	☑	☑	LC
29.	*Phoenix paludosa*	Arecaceae	☑	☑	☑	NT
30.	*Pemphis acidula*	Lythraceae	N/A	N/A	☑	LC
31.	*Rhizophora apiculata*	Rhizophoraceae	☑	☑	☑	LC
32.	*Rhizophora mucronata*	Rhizophoraceae	☑	☑	☑	LC
33.	*Scyphiphora hydrophyllacea*	Rubiaceae	☑	☑	☑	LC
34.	*Sonneratia alba*	Sonneratiaceae	☑	☑	☑	LC
35.	*Sonneratia apetala*	Sonneratiaceae	☑	☑	☑	LC
36.	*Sonneratia caseolaris*	Sonneratiaceae	☑	☑	☑	LC
37.	*Sonneratia* hybrid	Sonneratiaceae	☑	–	☑	EN
38.	*Sonneratia griffithii*	Sonneratiaceae	☑	☑	☑	CR
39.	*Xylocarpus granatum*	Meliaceae	☑	☑	☑	LC
40.	*Xylocarpus moluccensis*	Meliaceae	☑	☑	☑	LC

LC least concern, *DD* data deficient, *NT* near-threatened, *VU* vulnerable, *EN* endangered, *CR* critically endangered
(☑) present, (N/A) absent, and (–) data deficient
Note: Modified from Giesen et al. (2006), Aung (2016), and Yong (2016)

Table 14.5 The species diversity indices of the study sites at different coastal regions in Myanmar (tree species ≥5 cm in dbh) by San (2020)

Mangrove region	Study site	Number of species	Diversity indices		
			Simpson (D′)	Shannon–Wiener (H′)	Evenness (E)
Rakhine (upper)	Coastal	14	0.79	1.83	0.69
Rakhine (upper)	Island	12	0.67	1.37	0.55
Ayeyarwady (central)	Coastal	16	0.51	1.18	0.43
Ayeyarwady (central)	Island	8	0.81	1.75	0.84
Tanintharyi (lower)	Coastal	12	0.83	1.93	0.78
Tanintharyi (lower)	Island	16	0.81	1.97	0.71

Fig. 14.2 Wild cat in the mangroves of Ayeyarwady delta (Photo: Hkun Lat)

Zöckler 2016). A total of over 230 species of birds were observed in Myanmar's mangroves (Zöckler and Aung 2019). The lesser adjutant stork *Leptoptilos javanicus* (VU), mangrove pitta *Pitta megarhyncha* (NT), and brown-winged kingfisher *Pelargopsis amauroptera* (NT) are characteristic flagship species and still present in good numbers in the southern mangroves in Tanintharyi but scarce in the delta area and largely missing in the Rakhine region. Mangroves and associated mudflats are also home to a number of migratory water birds. A total of more than 20,000 migratory water birds have been counted regularly in winter in the southern Tanintharyi mangroves and mudflats alone, and among these are several globally threatened water birds (Zöckler and Aung 2019). Among the reptiles such as snakes, crocodiles, and lizards, the most prominent examples are the estuarine crocodile

Crocodylus porosus and the mangrove monitor lizard *Varanus indicus* (Thorbjarnarson et al. 2000). Several species of marine and freshwater turtles live exclusively in the mangroves, for example, the mangrove terrapin *Batagur baska*, but this has no longer been observed in Myanmar's mangroves since the early 2000 (Platt et al. 2008).

There are limited comprehensive studies and observations of faunal diversity all over the Myanmar's mangroves. Just after the independence of Myanmar from the British colony, in the Ayeyarwady Delta Working Plan (1948–1957), the following compressive and detailed wildlife information were recorded.

Elephants There were two herds of elephants, among which some were tuskers. The elephants in the mangroves were smaller than those generally found in Myanmar and migrate to northern reserves in the hot season for freshwater and fodder. Their favorite foods were cane, *thinbaung*, *danon*, *thaing*, and *kyu*. No case of destruction of crops was reported. No shooting or catching licenses were issued. A few elephants inhabited the mangrove areas near Shwe Thaung Yan Beach in the delta, and they were said to come down from the nearby terrestrial forest range.

Monkeys There were three kinds of monkeys; myauktanga is a small type living near banks and catching fish and otters. The brown medium-sized monkey is myauknyo, living on the tree tops and eating tender shoots of danon, thinbaung, etc. Myaukmido is tailless, frequenting only deep jungle and eating fruits and shoots.

Sambhur, Barking and Hog Deer, and Wild Pig These were found in all reserves. In the cold weather of 1945, there was an epidemic among wild pigs, and several carcasses were found in Labyauk reserve.

Tiger These were no longer found but they were reported in Kamahuak, Pathi, Anuak Htawbaing, Yakhing aw, and Myauk taya areas in the working plan 1947–1948 to 1956–1957.

Crocodiles They were fairly common and found in quiet places. The biggest measured some 14 feet in length. The Meinmahla Kyun Wildlife Sanctuary (MKWS) is intended for crocodile protection.

Others Hornbill, snipe, parrot, golden, plover, kingfisher, green pigeon, woodpecker, wild fowl, teal, wild cat, and rabbit are found in all reserves, whistling teal breeds in the delta. Spoon-billed sandpipers are also still found in Meinmahla Wildlife Sanctuary.

Site-specific faunal biodiversity can be observed in two exclusive mangrove parks, Meinmahla Kyun Wildlife Sanctuary (MKWS) and Lampi Marine National Park (LMNP).

According to the park management plan of MKWS, there exist 15 mammals including Ayeyarwady dolphin, monkey, and otter; 38 amphibians and reptiles including estuarine crocodiles and Burmese python, 186 bird species, 110 fish species, and 35 butterfly species have been recorded. The park supports globally threatened species such as the critically endangered hawksbill turtle (*Eretmochelys* *imbricata*) and mangrove terrapin (*Batagur baska*). Other threatened species include the endangered great knot (*Calidris tenuirostris*), Nordmann's greenshank (*Tringa guttifer*), green turtle (*Chelonia mydas*), and dhole (*Cuon alpinus*). Vulnerable species include the Pacific ridley turtle (*Lepidochelys olivacea*), fishing cat (*Prionailurus viverrinus*), lesser adjutant (*Leptoptilos javanicus*), and Irrawaddy dolphin (*Orcaella brevirostris*). It is also the last estuarine habitat in Myanmar for the saltwater crocodile (*Crocodylus porosus*).

The Lampi Marine National Park (LMNP) is the only marine national park in Myanmar. LMNP is located in the Myeik Archipelago. It is well known for its rich biodiversity and pristine and untouched mangrove habitats. Its management plan describes including 228 bird species, 19 of which are listed as threatened in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, including the plain-pouched hornbill and the Wallace hawk eagle, 10 amphibians and 19 reptile species, 3 species of sea turtles (the green sea turtle, the loggerhead sea turtle, and the olive ridley sea turtle), and 19 species of small, medium, and large mammals, 7 of which are in danger according to IUCN, including the Sunda pangolin and the dugong.

14.5 Ecosystem Services of Mangroves in Myanmar

Mangroves in Myanmar are predominantly found in the estuaries, deltas, lagoons, and coastal shorelines of all three main coastal regions. A total of ten provisioning, regulating, supporting, and cultural services were considered (Estoque et al. 2018), focusing on those that were believed to be of the greatest importance in economic and human well-being terms and drawing on the categorization of marine and coastal realm habitats and ecosystem services suggested in the Millennium Ecosystem Assessment (UNEP 2006). These ecosystem services accounted for are wood-based energy and timber, other sources of foods, fibers, medicines, coastal protection, hazard mitigation, regulation of water flow, regulation of water quality, mitigation of climate change, maintenance of fishery nursery populations and habitat, and recreation and experiential, cultural, amenity, and aesthetics. The goods and services are identified and evaluated as follows (Table 14.6).

Out of the ten ecosystem services provided by mangroves, the maintenance of fishery nursery and habitat has the highest value followed by coastal protection. The majority of the population on the coasts live with fisheries. In changing patterns of global climate and increasing vulnerability to tropical cyclones, the function of coastal protection to the lives and property of coastal communities is becoming a

Table 14.6 Values of mangrove ecosystem services of Myanmar modified from Emerton and Aung et al. (2013) and Estoque et al. (2018)

Ecosystem services	Components of ecosystem services in Myanmar	Ecosystem service value (ESV) (2018 USD)/ha/year
1. Wood-based energy and timber	Due to limited electricity access to the Ayeyarwady delta and remote coastal islands over Myanmar's coasts, local communities rely mainly on firewood and charcoal as fuel energy for their daily household consumption for cooking meals. Wood, posts, and poles for construction of local houses are also used from mangrove products. In addition, mangrove poles and posts can be utilized as fishing tools and fishing nets. Mangrove timber products are used widely around all three coastal tracts of Myanmar for subsistence though the availability of mangrove timbers is limited in quality and quantity	7.22
2. Other sources of foods, fibers, medicines, etc.	Non-timber forest products for food, fibers, medicine, etc. which are available directly or indirectly are provided from mangrove ecosystems. In the kitchens of local communities, they are always full of fishery products: fish, prawn, shrimp, crab, clams, mussels, etc. Local communities can extract the leaves of mangroves as foods. For instance, the leaves of *Acrostichum* species provide vegetables to make toast with fish pastes in everyday meals. Honey production from mangroves is also marketable. In addition, collection of barks from the woods of mangroves can be utilized as dyes. Nypa's leaves are used for roofing and walling. The shoots and fresh leaves from Nypa have become commercially and widely produced and exported for the production of medicines and cigars	2.89
3. Coastal protection	In degraded mangrove areas, riverbank and coastal erosion seriously occur while they are well protected in the protected areas of mangroves. The entangled aboveground root systems in mangrove communities, in particular, *Rhizophora* and *Avicennia* communities, protect coastlines during storm events as they can absorb wave energy and reduce the velocity of waves. Many species of mangroves also have extensive cable root systems which assist in binding sediment particles. The riverbanks and coastlines covered with mangrove	1369.28

(continued)

Table 14.6 (continued)

Ecosystem services	Components of ecosystem services in Myanmar	Ecosystem service value (ESV) (2018 USD)/ha/year
	communities are less likely to erode than unvegetated shorelines during periods of high wave energy	
4. Hazard mitigation	Myanmar is a cyclone-prone country. The western coasts and the Ayeyarwady delta suffer from tropical cyclones every year. The intensity of tropical cyclones has become more and more intense (change to "severe"), and the mangrove greenbelts can largely reduce its intensity. The shorelines covered with mangrove vegetation acted as an effective windbreak during the cyclone events, protecting leeward coastal settlements from intense storm damage, especially during the deadliest Cyclone Nargis 2008. Storm surge caused by Cyclone Nargis which hit the Ayeyarwady delta in early May 2008 caused about 140,000 casualties of death and damage to the economic sectors of coastal communities. During the impact of the cyclone, the "Meinmahla Kyun Wildlife Sanctuary" fully covered with mangrove vegetation saved thousands of local communities. Since the severe impact of the cyclone to the local communities, policy makers recognized the critical role of mangroves in protecting from the tsunami and cyclones and prioritized mangrove conservation and rehabilitation. Considerable mangrove afforestation is being done so as to minimize the damage to delta and coastal villages and agricultural land from the frequent and intense cyclones	349.01
5. Regulation of water flow	The prop roots of *Rhizophora apiculata* and the pencil-like roots of *Avicennia* species trap sediments and waste. In addition, flocculated clays are largely deposited within the mangrove zones of estuaries; many nutrients which are adsorbed onto the clay particles are also retained within the mangrove systems. This function of mangrove systems not only prevents the loss of nutrients from the catchment area to the sea but also removes the polluted wastes from the water column and stores them in the mangrove sediment. Plastic pollution is one of the major issues in the coastal regions of	275.27

(continued)

Table 14.6 (continued)

Ecosystem services	Components of ecosystem services in Myanmar	Ecosystem service value (ESV) (2018 USD)/ha/year
	Myanmar, and it blocks the river and stream flows in the mangroves in the proximity of urban areas	
6. Regulation of water quality	With their own local knowledge, the farmers in the Ayeyarwady delta traditionally prevent saltwater intrusion to their paddy fields by planting and maintaining mangroves along the rivers and stream banks close to their farms. Mangroves therefore provide two actions: the function of windbreak to absorb wind energy of tropical cyclones and the functions of mangrove roots and vegetation can also reduce the erosive tendency of water, enhance the formation of clay deposits, minimize the subsequent resuspension of these clay deposits, and trap the sediment particles and heavy metal deposits. In such ways, the quality of water in mangroves is improved. This sort of mangrove service helps when excess sediment is generated by human activities such as road construction, deforestation, mining, and large-scale concession of long-term cash crops	617.13
7. Mitigation of climate change	Mangroves are known to act as carbon sinks and have sequestration functions comparable with other ecosystems. Taking this opportunity, conservation and management of mangroves have been viewed as mitigation and adaptation of climate change. Nowadays, international organizations like WIF—Worldview International Foundation—have been implementing voluntary carbon standards (VCS) in progress for global climate change mitigation programs. Such a carbon mitigation program is associated with the livelihood improvement for local people. UNDP and FAO also started implementing mangrove projects associated with REDD+ and climate change adaptation while improving the livelihoods of local communities	304.64
8. Maintenance of fishery nursery populations and habitat	Globally marketable fisheries, in particular tiger prawns and mangrove mud crabs, are highly commercial. These fishery products are exported to China, Thailand, Japan, Singapore, and Europe. The basic needs	9122.45

(continued)

Table 14.6 (continued)

Ecosystem services	Components of ecosystem services in Myanmar	Ecosystem service value (ESV) (2018 USD)/ha/year
	and foods for mangrove-dwelling communities are fairly covered by these fishery products. Local communities are therefore highly aware of their traditional knowledge to maintain mangrove areas as the nurseries and habitats of fish, shrimps, crabs, etc. Most importantly, the food security for the communities and residents over the delta and coasts is largely covered by the fishery products from mangrove ecosystem services	
9. Recreation and experiential	Nature-based ecotourism has become one of the tourist attractions in the "Meinmahla Kyun Wildlife Sanctuary" in the Ayeyarwady delta to learn about crocodile nests and juveniles and do research on mangrove biodiversity as well as for educational purposes. The only marine national park with pristine mangroves "Lampi Marine National Park" is also another attraction of wilderness. Such mangrove estuaries provide food for the wildlife which inhabit the marine ecosystems and are the habitat of many wildlife species including water birds, crocodiles, tiger, wild elephants, monkeys, deer, and bees. Thus, mangroves and wetlands are "the so-called natural supermarket" for local communities because they support the coastal communities' food chain and rich biodiversity. Many countries earn income from ecotourism in the mangrove ecosystem. Rich biodiversity also attracts researchers to carry out more research activities in this pristine ecosystem. Unexpectedly, the current situation in Myanmar with "3C" by the political conflict, the pandemic of covid-19, and the civil war widespread has become a dilemma in developing this ecotourism sector, and its values is an estimated downward trend	475.97
10. Cultural, amenity, and aesthetics	Mangrove seascapes are significant to human well-beings for the relief of stresses and mental and physical health of people. Its associated ecosystems of coral reefs and seagrass also support its ecosystem services and values	28.46

key component in coastal regions of Myanmar. These ecosystem services, however, are not well recognized and undervalued by decision-makers. Awareness should be raised within decision-making processes in solving resource use and land-use conflicts.

14.6 Regeneration of Mangrove and Silviculture

The natural regeneration status of mangroves is largely influenced by the availability of seeds and propagules, existence of mother trees nearby, normal hydrology, tide and waves, and soil. The viviparous seedlings are already germinated while they are still attached to the mother plants and still receive nutrients from the mother tree (Panneerselvam 2008). According to the comprehensive study for all three main coastal regions in Myanmar (San 2020), it revealed that the occurrence of seedlings and saplings of the important species was inadequate in all study sites except the coastal study site of the lower coastal region, Myeik archipelagos. For all study sites, the number of species counted as natural regeneration was lower than that of the number of species recorded as trees with dbh $\geq$5 cm. The coastal study site of the central coastal region, the Ayeyarwady delta, was observed to have the poorest natural regeneration status, where the number of regenerated species represented only 50% of the recorded tree species. This could be the result of a smaller number of seed trees per hectare, extensive encroachment of weeds that outcompete seedlings in the initial stage of establishment, and a lack of tending operations after the Cyclone Nargis. Kairo et al. (2001) noted that the lack of mother trees leads to lower supply of propagules. It clearly indicates the requirement of silvicultural measures to create favorable conditions for seedling establishment in all mangrove regions over the coasts of Myanmar (Fig. 14.3).

14.6.1 Post-Cyclone Mangrove Regeneration and Reproduction

Myanmar is a cyclone-prone country, and the number of cyclones becomes frequent and intense not only in the Ayeyarwady delta but also along the whole coastal line, including the western Rakhine coast. The mechanisms of cyclone damage are related to a variety of factors, such as wind fields, wave energy, water levels, sediment dynamics, and chenier formation, all of which may affect the characteristics of mangrove sensitivity to a greater or lesser extent (Paling 2008; Cahoon and Hensel 2002). Accordingly, the wind-induced damage was observed as a key driver in changing patterns of post-cyclone mangrove regeneration and reproduction. In terms of wind damage, the sensitivity of the Rhizophoraceae and the resilience of

Fig. 14.3 Epicormic sprouts of *Heritiera fomes*, two and half years later after Cyclone Nargis (Photo: Toe Aung)

the Avicenniaceae have also been noted in Australian mangroves that were subjected to cyclones (Woodroffe and Grime 1999; Smith and Duke 1987). There are also very few Rhizophoraceae in the Sundarbans, and this may be because the adjacent Bay of Bengal receives 30–40 typhoons a year. A study on the cyclone-affected mangroves reaffirmed that *A. officinalis* has shown its greatest ability for vegetative reproduction whereas most Rhizophoraceae species had no vegetative reproduction (Aung et al. 2013). A study on epicormic sprouts on stumps from human impacts (Ono and Fujiwara 2004) also states that *A. officinalis* had more sprouts than did other species. According to Tomlinson (1986), mangrove Rhizophoraceae are distinctive because they lose the ability early to produce reserve meristems, whereas most other common genera (e.g., *Avicennia*, *Laguncularia*, and *Sonneratia*) retain reserve meristems and develop epicormic sprouts when damaged. It also seems probable that pioneer mangrove species, high light demanders, have the ability to produce abundant sprouts after natural disturbance. Aside from most Rhizophoraceae, most other species were also observed to have a considerable ability to produce vegetative shoots, although sprouting ability was not as high as in *A. officinalis*.

The measures to conserve, restore, and manage mangroves after cyclone disturbance, therefore, require understanding the regeneration and reproduction patterns.

Aung et al. (2013) showed that two communities of *B. sexangula* and *R. apiculata* shifted to *Avicennia officinalis* community, considerably farther from their pre-cyclone origins in ordinated space, compared to the others. Baldwin et al. (2001) indicates that moderately damaged mangroves were leading to single species stands, and severely damaged ones led to mixed species stands. Rashid et al. (2009) also report on the invasion of non-mangrove species after catastrophic disturbance. The years following the impact of a cyclone are challenging for mangrove species, as they compete with a number of herbaceous invaders and other opportunists. Therefore, species that are fast growing and demand a lot of light appear to have higher potential for competing successfully with invader species. The mangrove regeneration after the storm disturbance relying primarily on seedling recruitments has also been noted (Smith et al. 1994; Cahoon and Hensel 2002).

Mangroves, therefore, affirm their resiliency with high potential regeneration. With respect to the reason for recovery delay, Milbrandt (2006) states that delays in forest recovery are possible in severely impacted areas if either the delivery of propagules or the production of seedlings is reduced by habitat fragmentation. Most of the catastrophic disturbances have occurred neither by massive die-offs nor by parasitic infections; the real chronic ecological degradation has been proven when humans mismanage the systems and allow irreversible environmental changes from which recovery is almost impossible. It can be concluded in the post-cyclone mangrove regeneration, then, that mangroves can recover from catastrophic cyclone impact within a short period of time, with the exception of the *Rhizophora* genus, found to have been affected by intense winds (Aung et al. 2013).

14.6.2 Silvicultural Implication After the Cyclone Disturbance

Experience from coppicing true mangrove species will be used for depleted mangrove forests, especially in mangrove community forestry in the Ayeyarwady delta. The higher regeneration capacity with sprouting and coppicing should be tested as plantation models for beginning coppicing operations in mangrove community forestry programs that support the quick production for firewood demand. For example, *A. officinalis*, *H. fomes*, *S. caseolaris*, and *E. agallocha* have good potential for coppice management practices in community-based projects; *H. fomes* is also appropriate for coppice management (Aung et al. 2009; Ono and Fujiwara 2004). However, some of the Rhizophoraceae species should not be recommended for coppicing management operations. Whether or not silvicultural intervention is needed for post-cyclone mangroves is important for both foresters and ecologists. Following such disturbances, the persistence of non-mangrove species, mangrove-associated species, and invasive species, rather than true mangroves species, is easy to invade in large gaps and so could lead to critical ecological degradation and biological invasion. Most of the mangrove species have such patterns of release and

Table 14.7 5R—recovery index—based on four factors (Everham and Brokaw 1996) and one added factor with environmental risk (Aung 2012)

Community	Recovery factors			Risk factors		Recovery index	
	Recruitment	Release	Resprouting	Repression	Retreat		
A. officinalis	5	4	5	3	1	3.50	+++++
B. sexangula	5	3	0	5	0	1.60	++
E. agallocha	0	1	3	4	0	1.00	+
H. fomes	0	3	4	3	0	2.33	++
R. apiclata	0	1	0	3	3	0.17	-
S. caseolaris	1	1	4	1	2	2.00	++

Note: 0 for no recovery, and the higher the values, the more rapid the recovery of each community

wait for the canopies to open, after they incur certain kinds of crown damage either from natural disturbances, self-thinning, or proper harvesting. In addition, Imai et al. (2006) state that having many large gaps may help seedlings and saplings of *Sonneratia alba* and *Avicennia alba*, which need sunny conditions for their growth.

Aung et al. (2013) showed that the species-specific levels show different recovery pathways, although mangroves are generally highly resilient. *B. sexangula* and *R. apiculata*, which belong to the Rhizophoraceae group, were found to be more sensitive to natural disturbance, presumably wind-induced impact, while the other species showed more resilience. In the *Rhizophora*-dominated community, it is the indirect rather than the direct consequences of cyclones that slow the recovery process of these species-dominated sites. Management intervention in the cyclone-sensitive communities might be necessary in order to mitigate the adverse effects of catastrophic disturbances such as erosion and invasion by herbaceous species. To summarize, most mangrove species rely strategically on natural recovery processes and patterns, but for conservation purposes, attention should be paid to some sensitive communities suffering indirect, negative consequences following cyclones (Table 14.7).

Unlike other terrestrial forest species, mangroves are rarely treated with intensive silviculture operations. It might be due to the purposes of fuelwood production, reserve forests in the past, and windbreak and biodiversity conservation as the current trend. Most of the silvicultural operations are aimed to raise the regeneration such as regeneration improvement felling (RIF), pruning, coppice management, thinning, canal clearance, hydrological modification, gap planting, and weeding. In order to produce firewood and domestic use of poles and posts, the most common silviculture operations used by the mangrove community forestry areas are RIF and pruning. Taking advantage of the high capacity of mangrove species in regeneration and vegetative reproduction such as *Heritiera fomes* and *Avicennia officinalis* that produce quality wood and charcoal, coppice management is recommended to be widely practiced both for the protected public forests and community forests.

14.7 Global Climate Change and Mangroves

Observed changes in the climate for Southeast Asia include increasing temperature, variable precipitation, sea level rise, and an increase in the frequency and magnitude of extreme weather events (MONREC 2019). It has been revealed that Myanmar's climate is changing with certain observable trends over the last six decades (Hijioka et al. 2014). It shows an increase in mean temperature (~0.08 °C per decade), increase in overall rainfall (varying between 29 and 215 mm per decade throughout the country) with a declining trend in some areas, late-onset and early termination of southwest monsoon, increase in extreme weather events, and sea level rise. A closer look at observed data reveals that intense rainfall events are experienced with shorter monsoon period, and extreme events like destructive cyclones make landfall over Myanmar coastline every year as compared to typically once in three years during the twentieth century. Some key observed extreme events are presented below:

- An increase in the intensity and frequency of cyclones and strong winds: From 1887 to 2005, 1248 tropical storms formed in the Bay of Bengal. Eighty of these storms (6.4 % of the total) reached Myanmar's coastline. Cyclones Mala (2006), Nargis (2008), and Giri (2010) were the most severe and damaging cyclones experienced in Myanmar.
- Rainfall variability including erratic and record-breaking intense rainfall events: Every year Myanmar experiences intense rainfall. From July to October in 2011, there was heavy rain and flooding in the Ayeyarwady, Bago, Mon, and Rakhine regions.

Projected climate changes include the following:

- An increase in the occurrence and intensity of extreme weather events includes cyclones/strong winds, flood/storm surge, intense rains, extreme high temperatures, drought, and sea level rise.
- Table 14.8 presents the initial results of climate change projections based on the PRECIS model.

14.7.1 Cyclone Nargis

The changing condition of frequent and intense storms exacerbated by climate change scenarios would affect the coastal population in Myanmar more severely. Cyclone Nargis in May 2008 was the worst natural disaster in the history of Myanmar and the most devastating cyclone to strike Asia since 1991 (TCG 2008). It was also the tenth deadliest cyclone in the world on record (www.wunderground.com) and had significant effects on 37 townships in which most of them are mangrove areas in the Ayeyarwady delta and Yangon Coast. The effects of cyclonic winds were compounded by a 3–4-m storm surge and left almost 140,000 people dead and missing in the delta (TCG 2008). Mangroves are the only high-structure

Table 14.8 Climate change projection in coastlines where mangroves are common

Climate change predictions for 2001–2020 include	Climate change predictions for 2021–2050 include	Climate change predictions for 2051–2100 include
• An increase in temperature of ~ 0.4 °C–0.7 °C across Myanmar with the Ayeyarwady deltaic region experiencing the greatest increase (~0.7 °C) • Highly variable rainfall changes throughout the country including large increases (~228 mm in annual average volume) in the northern Hilly region as well as decreases (~58 mm annual average volume) in the Rakhine coastal, Yangon deltaic, and southern Tanintharyi coastal regions	• An increase in temperature of 0.8 °C–1.4 °C across Myanmar with the Yangon deltaic (1.4 °C) and Rakhine coastal regions (1.2 °C) experiencing the greatest increase • An increase in rainfall across the country with the Rakhine coastal region experiencing the greatest increases (~661 mm in annual average volume) and the eastern Hilly region experiencing the smallest increases (36 mm/annum)	• An increase in temperature of 2.8 °C–3.5 °C across Myanmar with the highest increases in the Rakhine coastal and Yangon deltaic regions (3.5 °C) • An increase in precipitation with highest increases (~1582 mm in annual average volume) in the Rakhine coastal and smallest increases in the eastern Hilly region (~209 mm in annual average volume)

vegetation thriving across the tropical coastline and in this context largely reduced the intensity of storms. Since the tragic lessons learnt from such deadly cyclone on the Ayeyarwady delta, Myanmar is now trying to protect its coastline with greenbelts. The protected public mangrove forests are increasingly being established. For instance, Yangon Region where there were no protected mangroves before now has its coastline protected with newly accrued mangroves by constructing natural infrastructure and greenbelts.

Mangroves in the newly accrued land are well planned to conserve for the protection of vulnerable coasts along the Mottama Gulf in Yangon Region.

14.8 Livelihoods

The majority of the coastal communities depend upon fisheries and agriculture, with the minority living on tourism and industrial development. The major livelihoods in the mangrove areas of Ayeyarwady delta can be categorized into (a) agricultural people, (b) fishery people, and (c) casual labor people (JICA 2005). Farmers are also used to domesticating buffalo, duck, chicken, and fish. A number of coastal communities suffer from poverty and a lack of viable livelihood options (Han 2010).

14.8.1 Fisheries

Mangrove areas fall in inshore fishery zones that are within five nautical miles from the shore along the Rakhine coast and ten nautical miles from the shore for the

Ayeyarwady and Tanintharyi coasts (MFF 2016). Fisheries, in particular artisanal fisheries, are the major livelihoods for local communities in mangrove areas. Fishery people in the mangrove areas can be seen as two types: full-time and part-time fishery people. Full-time fishery people earned much more than the high-income farm groups, while part-time fishery households (landless households) engaged in crab catching on a subsistence basis. The majority of small farmers and landless households also work as agricultural laborers during the peak agricultural season as the average daily wage rate increases.

The mangrove areas in other coastal areas have similar livelihoods to the Ayeyarwady delta. In Rakhine, poverty is the highest incidence in Myanmar. According to a World Bank analysis in 2014, the poverty in Rakhine is 78% compared to a national average of 37.5%. Due to low levels of land ownership and income in the state, 63% of the population depends on casual labor as a source of income, with agriculture followed by fisheries being the main sectors employing casual laborers. An assessment by REACH (2015) in the coastal districts of Maungdaw, Sittwe, Pauktaw, Minbya, and Myebon in northern Rakhine found that 85–88% of households live in storm-vulnerable housing constructed with only thatched roofs.

In the Myeik Archipelagos of the Tanintharyi coast, the Moken, also called sea gypsies or Salone in Burmese language, who live their traditional nomadic lifestyles are solely dependent on fishing and harvesting of sea cucumbers. It is estimated there are approximately 1000 indigenous Moken in the Myeik Archipelago and adjacent areas of the Andaman Sea.

14.8.2 Mangrove Aquaculture Ponds

Production of marine fish through aquaculture is relatively small compared with production of shrimp from aquaculture in mangrove areas or production of wild caught marine fish (FAO 2003). Aquaculture is practiced largely in brackish water along the mangrove areas close to the sea and coastline. One of the highest incomes is derived from the livelihood of mangrove aquaculture ponds, which is largely extensive with limited semi-intensive ponds. Typically, farmers build low earthen walls around their mangrove area. To increase productivity, many farmers also put additional shrimp fingerlings and juvenile crabs into the ponds (GGKP 2020). Basically, the farmers do not feed the fish in the ponds; the crabs, shrimp, and fish depend on natural food that is carried in by river water and from adjacent mangroves. In the current typical mangrove aquaculture system, farmers use polyculture systems that include crab, shrimp, and other fish cultured together. Tiger prawns, orange-spotted groupers, greasy groupers, and soft-shelled crabs are cultured in pond farms in the mangrove areas.

In many areas, mangroves have been converted to aquaculture ponds, for instance, in the reserved mangrove forest of Wunbaik, Rakhine, a total of 1176 ha of mangroves has been converted to shrimp ponds since the 1980s (Stanley et al.

2011). As a result, there is a need to develop environmentally friendly aquaculture, sustainable aquaculture, as well as conservation measures for mangrove resources. Now, without cutting mangrove vegetation, mangrove-friendly crab fattening is being driven as one of the community support livelihoods by introducing to the community forest based enterprises (FD 2019a).

14.8.3 Mud Crab Catching

A significant number of landless farmers in mangroves depend on catching crabs in the mangrove areas, which is an important activity in coastal rural areas along the Myanmar coast. It is common for the landless people as their major livelihood.

14.8.4 Rice Cultivation

The mangrove areas have been converted to rice agriculture. A large part of the Ayeyarwady delta is submerged by brackish water. In the rainy season, the middle and upper parts of the Ayeyarwady delta are covered with water of zero salinity, almost freshwater. Rice cultivation, therefore, is a major livelihood in the Ayeyarwady mangroves. It is reported that 98% of mangrove deforestation (Giri et al. 2008) was cleared and converted to other land uses for agriculture, in particular rice fields. Richards and Friess (2015) stated that 87.6% of the Ayeyarwady mangroves have been converted to paddy cultivation. The different types of rice cultivation in mangrove areas are found in Rakhine State, in which the rice cultivation and shrimp farming are alternatively carried out season by season. It is locally called "Kari." In the rainy season, farmers use their lands as rice fields and then in other open seasons, as shrimp ponds. However, such rice cultivation and extensive shrimp farming culture are rarely found in the mangrove areas of Tanintharyi as local communities in Tanintharyi are likely to depend more on marine and fishery resources.

14.8.5 Fuelwood

Fuelwood is the major energy source for domestic cooking in mangrove areas and buffer zones in the delta. It is also one of the major products in mangrove community forestry as timber, posts, and poles are limited in community forestry areas. In Pyapon Township, mangroves also provide the energy used for drying fish on bamboo racks on the shore. Fuelwood, therefore, has long been a significant income source for the livelihood of local people even though most fuelwood is illegally logged from reserved forests and national parks in the delta (GGKP 2020). Most community forests are established on ex-agriculture lands by planting fast-growing mangrove species such as *Avicennia* species.

14.8.6 Mangrove Tourism

Tourism is one of the fastest-growing industries in Myanmar, especially since 1996 when the Myanmar government promoted a tourism campaign *Visit Myanmar Year*. The number of tourists visiting Myanmar demonstrated a growing trend in the past 5 years, and in line with this, the EU declared that Myanmar is the 2014s world's best travel destination, indicating increased interest in Myanmar tourism. The Lampi Marine National Park in the Myeik (Mergui) Archipelago is one of many national parks the government wishes to promote as places to visit. The local people, the Moken, are glamourized in the western press as "sea gypsies" (Zöckler and Aung 2019).

In the Ayeyarwady delta, the Meinmahla Kyun Wildlife Sanctuary, the ASEAN heritage park, is also one of the nature-based tourism sites. Recently, the mangroves associated with the well-known beach such as Chaung Tha and Shwe Thaung Yan have become tourist-attractive sites. Mangroves and its associated coastal ecosystems, corals and dunes, marine life, and Moken culture are the main tourism attractions. War Kyun resort and its mangroves are tempting for nature-based tourists. Although there is a potential site of mangrove tourism in Rakhine State, Wunbaik Mangrove Reserve, the region has long been under security risk. Recently however, after the political conflict from February 2021, as well as the covid-19 pandemic, the tourism industry has been sharply in downturn.

14.9 Threats and Conservation

14.9.1 Threats

14.9.1.1 Fuelwood and Wood Products

Demand for firewood is not just in mangrove areas but also in the whole forest sector in Myanmar. According to the development of Asian countries, by 2015, electricity use per capita has been the lowest capacity among Asian countries. Currently 69.2% of households are still dependent on the consumption of fuelwood and 11.8% on charcoal. In terms of mangroves, it is locally said that more than half of the mangroves have been degraded and depleted due to fuel consumption since three decades ago. Electricity shortage in the capital city, Yangon, caused an increase in consumption of fuelwood produced from the mangroves in the Ayeyarwady delta. Charcoals produced from *Rhizophora* species were one of the best at that time, but now those species have become rare.

According to firewood surveys, 5 tons of fuelwood per household per year for rural communities from 20 villages in the vicinity of the project site are consumed by local communities (JICA 2017). At the same time, the 10-year Pyapon district forest management plan has shown that the consumption of fuelwood in Bogale Township is 2.5 tons of fuelwood per household per year for rural communities and 1.4 tons for urban communities. In fact, the primary purpose of mangrove-reserved forests in the first delta working plan was to provide fuelwood and basic needs, like poles and posts for construction, for local people who settle in the area no farther than 5 miles from the reserved forests. However, with increasing population density, the mangroves cannot afford the demand and supply as there is no electrification and limited alternative substitute fuels. The Ayeyarwady delta is the most populated region in Myanmar according to the Population Census (2014). Then, because of the overexploitation of firewoods not just for local needs but also trade and commercial purposes, the remaining patches of mangroves have been intended for conservation and biodiversity.

More seriously, high demands of firewood by offshore fishing rafts can accelerate the degradation of mangroves in the winter season as people increasingly collect firewood and sell them to the whole sale at the corresponding points in the villages. Without fulfilling such high demands and seeking alternative fuels, the sustainability of mangroves will fail. In reality, 3–5 years after the mangrove plantations were established by the Forest Department and other national/international organizations, the immature plantations happen to be cut for firewoods both for basic needs and commercial purposes. Regarding national policy upon solving the demands of firewood, NDC's (nationally determined contribution) commitment by Myanmar is to distribute 260,000 efficient stoves by 2030 and to establish community forestry to reach 2.27 million acres by 2030. However, there exist a number of challenges to accomplish these targets, and a strategic plan is needed for real implementation on the ground.

14.9.1.2 Rice Fields, Shrimp Farming, and Salt Pans

Encroachment of rice fields on the mangroves of the Ayeyarwady delta is common, and 87.6% of mangroves that have been already cleared are due to rice fields (Richards and Friess 2015). For instance, in one of the reserved mangroves in the Ayeyarwady delta, 69.35% of mangroves were lost by 2015 from 1990, and most of them, were due to rice fields. The mangrove areas are rich in nutrients, and part of larger wetland systems, making them attractive as agricultural areas. Local communities have limited choice to earn their living by other alternative job opportunities, and clear cutting mangroves and cultivating rice are supposed to be the only livelihood they rely on. In fact, local people have been quite aware of mangroves for their support to the society as fishery breeding ground and coastal protection functions. However, they need short-term benefits and cannot wait for long-term intangible benefits from mangroves to address their immediate needs. In the past, mangroves were supposed to be wastelands with unproductive muddy flats and

Fig. 14.4 Extensive shrimp pond in the Ayeyarwady mangrove (Photo: Toe Aung)

mosquito breeding grounds and thus cleared to expand rice fields for rice production campaigns by the corresponding ministries in coordination with development partners. Big dykes were constructed to block the intrusion of salinity. This made the mangrove areas unregulated by the flow of brackish water, and after that, the survival of mangroves was no longer viable.

Similar to encroachment of rice fields, shrimp farming by clearing mangroves is another major concern (Fig. 14.4). This aquaculture is intended to produce tiger prawns, but the extensive aquaculture operations are most often constructed for export. In Rakhine State, both rice cultivation and shrimp farming are carried out seasonally and alternatively. Especially, at the southern border of Pyindaye reserve mangroves in the Ayeyarwady delta, a couple of thousand acres of mangroves have been cleared for shrimp farming practices. Shrimp farm activity alone has been responsible for the loss of 38% of the world's healthy mangroves; the percent climbs to 52% if all agricultural activities are counted (Ellison and Farnsworth 1996).

The mangrove areas in the Ayeyarwady delta and Rakhine State are prized for salt production in particular due to their closeness to the sea. The salt production is granted for license by the mining sector. The lands, although covered with mangroves, are managed out of the permanent forest estate (PFE) but are prone to change into other land uses. As a result, large areas of mangroves have been cut, and the hydrology has been disrupted to intensify commercial production of shrimp and other species, cultivate agricultural crops, and create salt ponds.

14.9.1.3 Climate Change and Natural Disasters

According to the Munich Re's 2015 Global Climate Risk Index, Myanmar is ranked the second highest cyclone-vulnerable country in the world. UNEP (2013) describes (a) an increase in mean temperature (~0.08 °C per decade) with the prevalence of drought events; (b) an increase in the intensity and frequency of cyclones and strong winds; (c) an increase in overall rainfall with a declining trend in some areas and late-onset and early termination of the southwest monsoon, with rainfall variability including erratic and record-breaking rainfall events; (d) an increase in the occurrence of flooding; and (e) an increase in extreme high temperatures. Under such a climate risk situation, Cyclone Nargis 2008 is the deadliest storm in the history of Myanmar. The livelihoods of local people were severely affected, and the mangroves were also destroyed. The mangroves had also been devastated by the cyclone, but the impacts seemed to be more severe near human interventions. The possible reason is that the ecosystems of mangrove are dynamic and highly resilient (Alongi 2008), and the mangrove vegetation resilience after the cyclone has also seen high recovery. Local people had high demands of wood to reconstruct their shelter/houses, and their cuttings of mangroves at that time were neglected without law enforcement. In spite of the fact that there is no data to be approved, the woody vegetation of mangroves in the Meinmahla Kyun Wildlife Sanctuary has significantly changed to bush and scrub vegetation after Cyclone Nargis.

14.9.1.4 Coastal and Delta Development with Human Settlement

The landscape of the Ayeyarwady delta has for a long time been without systematic urban and rural planning and an integrated approach. Sectors have been disintegrated with limited coordination. The overlap of freshwater fishery law and forestry law has not been solved yet. The enforcement of forestry law is weak because of insufficient human and financial resources for effective conservation and management measures. Although the mangroves have been reserved for many decades, illegal encroachment of rice fields has not been well prohibited, and illegal activities are still carried out.

Land-use conflicts among forestry, fishery, and agriculture have been due to unclear land-use policy. The MOECAF (Ministry of Environmental Conservation and Forestry) (now MONREC) led the reformulation of national land-use policy, and it was issued in January 2016 but needs to be implemented on the ground by relevant authorities and by decision-makers. There are two major concerns from landscape perspectives: one, erosion is seriously happening along the tributaries, streams, and rivers, and two, the villages settled along the highly eroded riverbanks and wind-exposed environment without windbreak or green shelter. Thousands of people died in Cyclone Nargis, and it is commonly said among local communities to be due to the clearance of mangroves in the reserved mangrove forests.

14.9.1.5 Improper Revenue Collection System

Inside the mangroves in Myanmar, nonwood forest products (NFWPs) are allowed to be extracted for basic needs and commercial use. Revenue collection is one of the hidden issues in mangrove deforestation. The revenues collected from each area should be followed in line with the actual production of the NWFPs. If not so, more pressures of cutting mangrove resources for fuelwood, posts, poles, and timber demands cannot be addressed. For *Sonneratia* and *Avicennia* species planted in the project, the size of girth gained for 5–7-year-old plantations is harvestable in favor of illegal cuttings. Decision-makers need to be aware to stop excess revenue collections from fuelwood, poles, and posts on mangrove resources in improper ways. Therefore, revenue collection needs to be carefully dealt with in practice. Positively, in recent years, the planned revenue collection from mangrove resources has been reduced, which support restoration of mangroves naturally from serious degradation. It should be hereby noted that mangroves should be intended for conservation rather than production-based management because of its high ecosystem productivity and values.

14.9.1.6 Grazing

Grazing in mangrove areas is not seen as a serious issue to be addressed. However, the restored mangrove plantations are at risk of grazing buffaloes in some parts of the Ayeyarwady delta. The species mostly consumed and grazed are *Avicennia officinalis* and *A. marina*. Overgrazing by goats, camels, etc. is one of the common disturbances in the Middle East countries (Lewis 2006).

14.9.2 Conservation and Management

Since the British colonial days, the mangroves in Myanmar have been managed within the permanent forest estate (PFE) that includes reserved forests, protected public forests, and protected area systems. The mangrove area extent in Myanmar is estimated at approximately 1,119,284 acres (FAO 2020), in which the permanent forest estate has been established as 657,983 acres; approximately 59% of mangrove cover over the Myanmar coasts (FAO 2020) (Forest Department, 2020 unpublished). The rest of the mangroves (41%) is out of the permanent estate, and it has been at risk of land grabbing for long-term cash crops, resorts, and shrimp farming. According to the Forest Department figures (unpublished 2020), the total mangrove PFEs are 657,983 acres: 88,106 acres in Rakhine State, 228,740 acres in Tanintharyi Region, 334,917 acres in Ayeyarwady Region, 6089 acres in Yangon Region, and 131 acres in Mon State. In Yangon Region and Mon State, there were no protected public mangroves until 2015, and the protection of mangroves has been raised by the claim of local communities to protect their lives from the tropical cyclone. However, like the mangroves in the Ayeyarwady delta and Rakhine State, these mangrove PFEs are facing a lot of challenges in deforestation and fragmentation due to the encroachment by the increasing population. Since 1995, community-based mangrove management, called "community forestry," has also been initiated, and now the establishment of mangrove community forests has been issued to more than 10,000 acres.

Mangrove-protected area is also one of the PFE types. There are two mangrove-protected areas: one in the Ayeyarwady delta and one in the Myeik Archipelago. Comparing the reserved forest and protected public forests in mangroves, mangrove-protected areas have shown as more effective management perspectives with reference to the experiences derived from the impacts of Cyclone Nargis in 2008. One of the mangrove-protected areas called "Meinmahla Kyun Wildlife Sanctuary" established in 1993 was fully covered with mangrove forests. It supports one of the largest remaining mangrove areas in the delta, where mangrove ecosystems have declined due to the major activities of rice cultivation and human settlement, although most of the true mangrove species have been already replaced by mangrove date palm (*Phoenix paludosa*). It is also a Ramsar Wetland of international importance, representing an ASEAN Heritage Park, as well as its substantial carbon sequestration capacity and supporting globally threatened species such as the critically endangered hawksbill turtle (*Eretmochelys imbricata*), mangrove terrapin (*Batagur baska*), and the last estuarine habitat in Myanmar for the saltwater crocodile (*Crocodylus porosus*), it holds significant cultural and historic value, a kind of spirit, locally called "U Shin Gyi Nat" according to the myths and pilgrimages for local communities living in the brackish water environment, that is largely related to the mangrove environment.

Another mangrove-protected area is located in the Myeik Archipelagos, called "Lampi Marine National Park," which was established in 1996 that covers a group of islands in the Myeik Archipelago in the Tanintharyi Region of southern Myanmar. It is the only marine national park with richness in coral reefs, seaweeds, mangroves, and seagrass beds which are important food for threatened species such as the green sea turtle and the dugong.

14.9.3 Afforestation

Recently the Myanmar Reforestation and Rehabilitation Plan 2018 to 2027 by the Forest Department has started establishing more mangrove plantations all over Myanmar coasts. Its target for 10 years is set to establish almost 29,690 acres, meaning 3000 acres of mangrove plantation every year in the degraded and depleted mangroves over Myanmar coasts. Planting mangroves started in 1982, and the total number of mangrove plantations until 2020 is 62,260 acres in the Ayeyarwady delta since 1982, 3145 acres in Rakhine coastline since 2007, and 550 acres in Mergui archipelagos in Tanintharyi coastline since 2014. Mangrove plantations are aimed to

Fig. 14.5 Propagule collection and sale by the mangrove community forestry (Photo: Myo Myint)

restore mangrove ecosystems in the depleted mangrove areas, fulfill the subsistence needs of local communities, improve the health of the natural environment, establish mangrove windbreaks for the safety of local communities, and adapt the livelihoods of local people in harmony with climate change. The success of mangrove plantation, however, is questionable and needs to be evaluated.

Planting with seed pots in plastic bags is common in mangrove plantation establishments, and it is also a current method with standard norms for the mangrove plantation by the Forest Department. INGOs (international nongovernmental organizations) and NGOs (nongovernmental organizations) working for mangroves are also planting in a variety of ways such as direct seed sowing, direct seeding of propagules, and bare root planting. The interesting thing to note for mangrove planting is that a million of wild seedlings were unofficially used in a thousand acre of mangrove plantation establishment after Cyclone Nargis. It could be considered one of the natural and cost-effective ways of mangrove planting if caution is taken not to disturb the surrounding natural mangrove flora and fauna. For the community forestry user groups in the Pyapon Township in the Ayeyarwady delta, selling mangrove propagules for the mangrove planting agencies has become one of their major livelihood's incomes (Fig. 14.5).

14.9.4 Legislation

The National Forestry Master Plan (NFMP) formulated for a 30-year period from 2001–2002 to 2030–2031 partly cover mangrove conservation and management. Accordingly, Community Forestry Instructions' (CFIs) issued FD (1995) is a remarkable initiative in the aspects of partnership, participation, and decentralization in managing the forests including coastal forests and mangroves in Myanmar. The instruction grants the local communities' trees and forest land tenure rights for an initial 30-year period that is extendable based on the success of implementation. The FD provides technical assistance and plays the leadership role in the exercise of community forestry. To promote mangrove conservation, restoration, and management, MONREC (Ministry of Natural Resources and Environmental Conservation) is the main agency responsible for implementing the national policy on nature conservation in Myanmar; however, other ministries, such as the Ministry of Agriculture, Livestock and Irrigation (MOALI), also share responsibility and accountability for biodiversity conservation. In this context, the National Coastal Resources Management Committee (NCRMC) has been recently formed in an attempt to consolidate marine and coastal resources conservation activities, largely focusing on mangrove ecosystems conservation, at local and national levels. The committee is chaired by the vice president (1) and includes 21 members, thus being one of the most important platforms for mangroves and its associated marine and coastal ecosystem. Table 14.9 shows the enabling legal framework that supports the mangrove sector development and conservation.

14.10 Case Study: Perspectives of Awareness, Attitudes, and Participation of Local Stakeholders in Mangrove Ecosystem Conservation and Management

14.10.1 Background

Humans cannot live just for themselves; instead, they live and support each other and gather with other species in the ecosystem (Sudarmadi et al. 2001). However, they are becoming densely populated and exploit natural resources unwisely, with the net effect that they now have to confront the critical problem of environmental degradation. As one of our major environmental concerns, mangroves are disappearing at a rate greater than or equal to the adjacent rainforests (Valiela et al. 2001), and their deforestation has become critical to be tackled in our time. The causes of the loss have been mainly attributed to anthropogenic activities (FAO 2007; Walters et al. 2008), such as conversion to agriculture, aquaculture, urban development, salt pans, transmission lines, and mining (ISME 2004). Humanity is therefore a major force in global change and shapes ecosystem dynamics ranging from local environments to the biosphere as a whole (Folke 2006).

Table 14.9 Myanmar's existing policies, strategies, and frameworks and main multi-/bilateral treaties and agreements

National development framework	Myanmar's market-oriented policy scheme (1988) Myanmar Agenda 21 (1997) Millennium Development Goals (MDG) (2006) National Sustainable Development Strategy (NSDS) (2009) 30-year National Forestry Master Plan (2001–2002 to 2030–2031)
Institutional framework	National Coastal Resources Management Committee (NCRMC), Working Committee, Advisory Committee, Coastal Regional/State Committees and Coastal District Committees Ministry of Natural Resources and Environmental Conservation ASEAN Committee on Disaster Management (ACDM) National Disaster Preparedness Central Committee (NDPCC)
Supporting policy and planning framework	Myanmar Forest Policy (1995) Community Forestry Instruction (1995) National Environment Policy (1994) Myanmar Action Plan for Disaster Risk Reduction (MAPDRR) (2009–2015) Myanmar Action Plan on Disaster Risk Reduction, Preparedness, Relief and Rehabilitation (2017)
Main treaties/agreements	United Nations Framework Convention on Climate Change (UNFCCC) (1992) Convention on Biological Diversity (CBD) (1994) The Kyoto Protocol (1997) Hyogo Framework for Action (HFA) ASEAN Multi-sectoral Framework on Climate Change Agriculture, Fisheries and Forestry towards Food Security (AFCC)

For most of human history, the natural world has been protected from most disruptive human influences by virtue of our relatively humble technology, local laws, and cultural or religious taboos, all of which have prevented overexploitation. The loss of traditional knowledge about resource use is one of the central problems of our time (McNeely 1993). Local environmental knowledge and awareness can be a powerful mechanism in mangrove restoration and management. Local people as "critical social capital" and the mangroves as "critical natural capital" have lived side by side for hundreds of years. Local people, without doubt, are of crucial importance in shaping their surroundings, and they can either destroy or create a better environment. The hypothesis in the case study is whether or not mangrove degradation is due to stakeholders being unaware of mangrove conservation.

14.10.2 Study Site

The communities in two separated mangrove tracts of mangroves, Pyindaye Reserved Forest (PRF) and Kadonkani Reserved Forest (KRF), are the focus of this case study. Both are next to the Meinmahla Kyun Wildlife Sanctuary, a totally protected area. Kadonkani RF was in the eye of the path of Cyclone Nargis in 2008 and was severely affected, while Pyindaye RF was outside the eye of the cyclone path and was less affected. Five villages in each were selected. The study villages in Kadonkani RF were Atwinmayan, Kyeinchaungkyee, Gwechaungkyee, Ngapokethin, and Padegaw, while those in Pyindaye RF were Anaukmee, Ashaepya, Gawdu, Htaungyitan, and Thameinpale. The population of the former five villages was subject to severe devastation caused by the cyclone. Figure 14.6 shows that almost half of the population in Kadonkani mangroves was decimated by the deadly cyclone, whereas the latter five villages in Pyindaye mangroves did not undergo any change to their social structure and there was no loss of human life.

The analysis was carried out by dividing awareness, attitudes, current participation, and future participation prospects based on location (the level of cyclone impact), gender, education, and livelihood or occupation. Data was generated by conducting semi-structured interviews with local respondents as well as through field-based observations. Based on the preliminary survey of the area, local

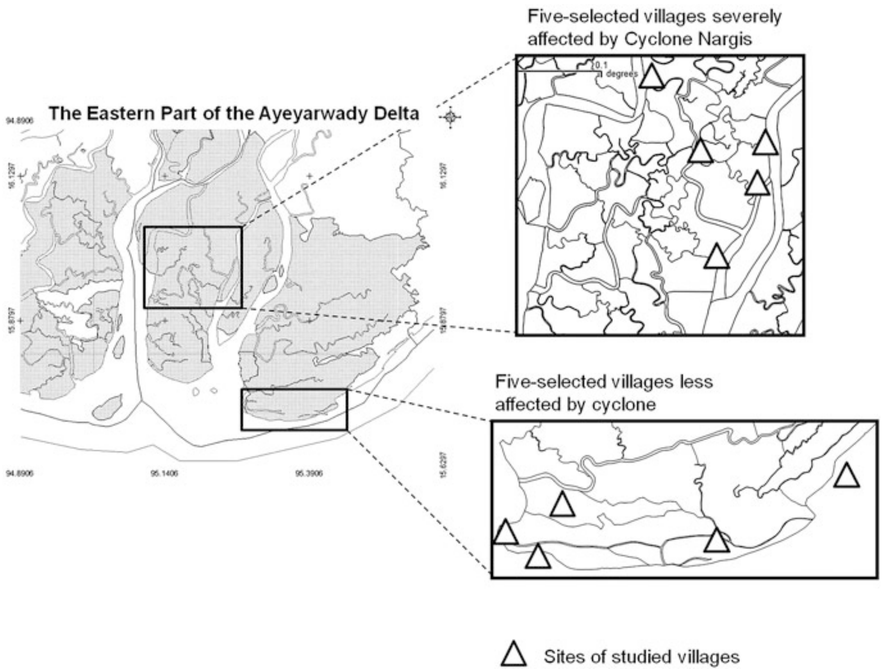

Fig. 14.6 Map showing the location of the study villages in the two separate regions

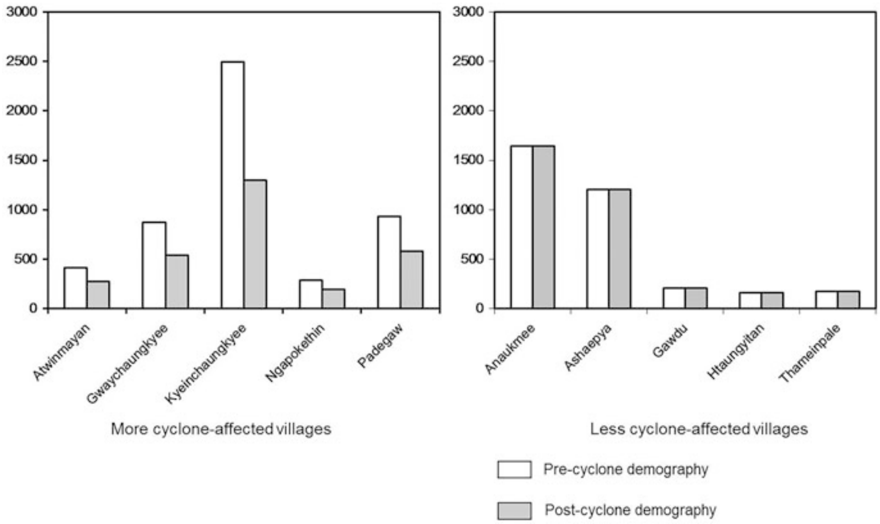

Fig. 14.7 Pre-cyclone and post-cyclone population sizes of five severely cyclone-affected villages in the Kadonkani mangroves and five less cyclone-affected villages in the Pyindaye mangroves

stakeholders were divided into six main categories according to their livelihood patterns, that is, fishermen, farmers, casual laborers, workers, shrimp pond owners, and salt pan owners. All of the groups are suggested as mangrove key stakeholders since they depend mainly on the mangroves either directly or indirectly (Fig. 14.7).

14.10.3 Awareness and Attitude on Diverse Livelihood Patterns

The results have shown that there is a significant difference between the two regions with their different cyclone impact extents while education, gender, and occupation were not considerably significant. Interesting results were derived from the observations of awareness and attitudes with the patterns of livelihood of local respondents, shown in Table 14.10. Awareness is highly significant among the different livelihoods, and after excluding workers, a null hypothesis was accepted. Therefore, the workers, that is, the outsiders or recently migrant people to the mangrove area, had the most limited awareness of the mangrove environment. In terms of attitudes, highly significant values were found among different livelihood patterns of people. The extent of the differences can be seen clearly, particularly for shrimp pond owners. It was evident that shrimp pond owners had a limited willingness to show the importance of mangrove conservation. Overall, despite the fact that there was considerable awareness and attitudes of mangroves by all local stakeholders, there

Table 14.10 Comparison of awareness and attitudes in terms of different patterns of livelihood

	Patterns of Livelihood												
	Farmers		Fishermen		Casual laborers		Workers		Shimp-pond owners		Salt-pan owners		
Awareness	Yes	Limited	Yes	Limited	Yes	Limited	Yes	Limited	Yes	Limited	Yes	Limited	*p*-value
Observation I	83	1	61	4	79	5	20	7	24	2	26	0	**0.0002***
Observation II	84	0	65	0	85	1	24	4	26	0	26	0	**0.0000***
Observation III	67	16	54	11	75	12	20	8	18	7	26	0	0.0523
Observation IV	78	6	60	5	81	5	22	6	24	1	26	0	0.0519
Observation V	84	0	65	0	86	1	28	1	25	1	26	0	0.3083
Attitude	Yes	Limited	Yes	Limited	Yes	Limited	Yes	Limited	Yes	Limited	Yes	Limited	
Observation I	83	0	64	0	83	3	23	3	25	1	22	2	**0.016***
Observation II	56	27	38	27	73	13	21	6	7	18	21	5	**0.0000***

Note: The significant differences (*$p < 0.05$) in awareness and attitudes are represented in bold. Variations in response rates are the result of missing answers or missing information in the answer sheets (Adapted from Aung (2012)) was a slight difference between the mobile communities and the immobile or settled ones.

Cornwall (2008) investigated that, in environmental awareness, there are significant differences in occupation, location, land tenure status, sex, caste, religion, or tribe, although they are related in different ways. However, the current case study of location, education, and gender was not considerably significant. It was hypothesized that the mangroves in the mega-delta region have been continuously decreasing because one of the factors is local people's lack of awareness about the mangroves. This assumption is rejected in the present case study; the majority of people living in the mangrove environment illustrated an appreciable level of knowledge and awareness about the mangroves. Their lifelong experience of the dramatic decline in the number of fish available to catch and the limited availability of fuelwood to meet their subsistence needs could have made them realize the value of the mangrove ecosystem. Most importantly, in 2008, their personal experience of Cyclone Nargis, the deadliest tragic story over the history of Myanmar, and the concomitant loss of human life and property were unforgettable. It is, therefore, not surprising that the majority of local respondents were aware of the crucial importance of the mangroves in terms of their life-supporting and life-protecting functions. However, in the present study, the key finding pertained to the recent migrants and remote resource users, that is, the mobile/migrant people, meaning not native to the current mangrove sites; in particular workers and shrimp pond owners have less awareness and attitudes compared to the immobile ones who have settled in the mangroves since at least a decade.

In terms of the workers, they seemed to be slightly less aware of the importance of the mangroves when compared to other local respondents. This community group, which comprises mostly recent migrants, relies partially on the mangroves because, although most of them are not direct mangrove cutters, they directly use the mangroves for fuel and construction materials. The second community group that showed limited attitudes compared to the other groups was the businessmen who operate shrimp farming. Some of them were reluctant to accept the importance of the mangroves as it was their perception that mangrove restoration and conservation would negatively affect their business. Mangrove habitats need to be cleared for the establishment of shrimp ponds, and the businessmen claimed that the shade of the mangrove canopy causes a decline in the shrimp production rate as well as a reduction in the size of tiger prawn (*Penaeus monodon*). This is a direct conclusion derived from their experience. This fact should not be supposed as a hindrance in mangrove restoration measures. The critical point here is how to draw up a strategic management plan that integrates both social and ecological needs of all relevant stakeholders.

With respect to the responses of local stakeholders, some are shown in Box 14.1, indicating that if restored mangroves were privately owned, the local stakeholders would have a greater desire to participate in restoration measures. According to Addun and Muzones (1997), there are five basic principles that are required for community-based resource management: empowerment, equity, sustainability, systems orientation, and gender fairness.

Box 14.1 Concluded Answers of Respondents with Respect to Questions About Their Restoration Participation Motivations and Limitations

Motivations to participate in mangrove restoration	Limitations to participate in mangrove restoration
• "If we plant mangroves, we can get shelter from storms in future" • "Planting mangroves can regulate the climate again" • "If the extent of mangroves increases again, fish, shrimp, and crabs will flourish once more" • "I would like to secure fuelwood and plants for household use in the future, so I want to plant mangroves" • "Under tree shelter, we have better lives" • "I do not want there to be scarcity of fuelwood, I want to plant mangroves" • "We want large adult trees to protect our lives from storms" • "It is our experience that, if we plant mangroves, they save our lives" • "(I want it) to be green again the same as before" • "We have to participate because we are asked to do it by organizations in force"	• "I have to struggle for my family's livelihood daily—if there is no income today, there is no food for tomorrow" • "Time is too limited to participate in planting because I have to go fishing" • "Not enough people at home to participate in the restoration" • "That is not private (ly owned)" • "Only if I can get that land privately, then I can protect it" • "Too busy doing my own business of fishing and farming." • "I am too busy with my shrimp pond business" • "I am not a man, just a widow, so it's difficult to take part" • "(There is) no household leader at home" • "I am not quite healthy (enough) to participate in planting activities" • "I am getting old"

The current case study first attempted to hypothesize that local people have limited awareness and attitudes with respect to the mangrove environment, and hence they did not actively participate in restoration processes. Indeed, we sought to establish that this factor was one of many reasons that caused the degradation of the mangroves. The hypothesis is rejected in the present case study as it was demonstrated that most of the local stakeholders have fairly sufficient awareness and attitudes to enable active participation in mangrove restoration although there are slight differences between the different stakeholders. In particular, poorer attitudes were observed in some migrant communities compared to the settled communities. This slight difference may not be an issue, and the key point is that restoration strategy through the participation of all local stakeholders is needed in order to restore, reforest, and rehabilitate the mangroves. However, local participation in restoration measures is still limited. In developing a management strategy, participatory management should be incorporated by prioritizing the subsistence needs of the local people plus economic benefits.

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Chapter 15
Mangroves of Malaysia

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Abstract This chapter on Mangroves of Malaysia begins with a brief introduction on the geography of Malaysia, consisting of Peninsular Malaysia, Sabah, and Sarawak separated by the South China Sea. Information on the population, land area, and area of mangroves in Malaysia is presented. The largest area of mangroves is in Sabah, followed by Sarawak and Peninsular Malaysia. Globally, Malaysia's mangroves rank sixth in country area after Indonesia, Brazil, Australia, Mexico, and Nigeria. In Malaysia, mangroves are classified into permanent forest reserves (PFRs) which consist of protection forest reserves, domestic forest reserves, mangrove forest reserves (MFRs), virgin jungle reserves (VJRs), and wildlife reserves. The other categories are state land mangroves and gazetted conservation areas. The other main sections of the chapter are Biodiversity; Livelihoods; Threats to Mangrove Ecosystems; and Restoration, Conservation, and Management. These sections are strengthened by six case studies. They include proboscis monkeys of Labuk Bay, Sabah; new genus and species of mangrove crab; mangrove wood carvings by the Mah Meri tribe; charcoal production in Matang, Peninsular Malaysia; wood vinegar production in Matang, Peninsular Malaysia; and long-term ecological research at Sepilok Laut, Sabah. These case studies highlight the sound management of mangroves in Malaysia. The section on Restoration, Conservation, and Management includes a success story of mangrove rehabilitation at Sungai ISME (International Society of Mangrove Ecosystems), a collaboration between the Sabah Forestry Department (SFD) and the International Society of Mangrove Ecosystems (ISME). Compared to mangrove rehabilitation projects in Kiribati and Gujarat implemented by ISME, the project in Sabah scores strongly in accessibility, collaboration, objectives, publicity, capacity building, voluntary participation, and sustainability. Learning from these examples

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can help in the development of a mangrove action plan (MAP) for Malaysia where a policy of integrated coastal management ensures the sustainability of mangrove ecosystems and their ecological services.

Keywords Case studies · Mangrove action plan · Mangrove rehabilitation · Matang · Permanent forest reserves · Sepilok Laut · Sungai ISME

15.1 Introduction

Malaysia has 4.7% of the world's mangroves, ranking sixth in country area after Indonesia (20.9%), Brazil (8.5%), Australia (6.5%), Mexico (5.0%), and Nigeria (4.8%) (Bunting et al. 2018). Malaysia comprises Peninsular Malaysia and East Malaysia states of Sabah and Sarawak, which is separated by the South China Sea. Malaysia's population in 2020 is estimated at 32.7 million (DoSM 2020), and this has more than doubled in the last 35 years. Malaysia's mangroves account for 2% (629,038 ha) of the total land area of Malaysia (329,847 km^2) with 110,953 ha (18%) in Peninsular Malaysia, 139,890 ha (22%) in Sarawak, and the largest area of 378,195 ha (60%) in Sabah. Maps showing the extent and distribution of mangroves in each state of Malaysia including Sabah and Sarawak have been published by Omar and Misman (2020). Table 15.1 shows the extent and decrease in mangrove area by region since 1990 (Omar and Misman 2020). Sarawak has lost the largest area of mangroves (8046 ha). Sabah still has 90% of mangroves intact (Tangah et al. 2020a).

Sabah's extensive mangroves occur mainly along the coastlines and river systems, of which 93% are within permanent forest reserves, with the remaining 7% on state land or alienated/privately owned land. Table 15.2 shows the classification of mangroves based on permanent forest reserves in Malaysia (NRE 2016). Most key mangrove sites in Malaysia are included in the permanent forest reserves (PFRs), that is, forests that are managed primarily as source of timber and non-timber goods (MoSTE 1997). PFRs come under the jurisdiction of the respective state governments. The term PFR, however, may be misleading since it implies that the forest areas are permanent. This is not guaranteed since the Executive Council within State Governments can degazette any area of the PFR for infrastructure development, agriculture, housing, or other purposes. The main factors for mangrove loss are due to conversion to other land uses such as agriculture (oil palm plantations) and aquaculture (shrimp ponds) (Tangah 2004; Omar and Misman 2020).

Table 15.1 Extent of mangroves in Malaysia from 1990 to 2017 (Omar and Misman 2020)

Region	1990 (ha)	2000 (ha)	2017 (ha)
Peninsular Malaysia	116,746	114,358	110,953
Sarawak	147,936	145,263	139,890
Sabah	385,630	382,448	378,195
Total	650,312	642,069	629,038

Table 15.2 Classification of mangroves in Malaysia (NRE 2016)

Status	Name	Forest function
Permanent forest reserves (PFRs)	Protection forest reserves	Forests conserved for the protection of watersheds and maintenance of stability of soil, water conservation, and other environmental factors. Logging is not permitted in these areas.
	Domestic forest reserves	The produce from these forests, including small amounts of timber, is for the consumption of local communities only, and commercial use is discouraged.
	Mangrove forest reserves (MFRs)	Forests for supplying of mangrove timber and other forest produce to meet general trade demands and multiuses.
	Virgin jungle reserves (VJRs)	Forests conserved strictly for forestry research purposes including biodiversity and genetic conservation. Logging is strictly prohibited.
	Wildlife reserves	Forests conserved primarily for the protection and conservation of wildlife. Logging is prohibited.
State land mangroves	Native land/commercial land	Largely, not protected for conservation and land is available for development. Non-gazetted land is also conserved for shoreline protection.
Gazetted conservation areas	National parks/ sanctuaries	Totally protected mangrove areas, gazetted as state park, bird sanctuary, nature reserve, or city/town park under various state laws

Mangroves are important multiple-use ecosystems as they provide a myriad of products and services that include productive, protective, and economic benefits to coastal communities (Spalding et al. 2010). Mangrove ecosystems are habitats and nurseries for a diverse variety of flora and fauna. Mangroves function as natural coastal barriers to safeguard against sea level rise and severe erosion and ensure shoreline stabilization, protection, and sediment and nutrient retention. Mangroves also play an important role in mitigating climate change since they store carbon as biomass and in the soil. Nevertheless, mangroves remain one of the most threatened habitats on earth. Understanding their true values will help in the long-term restoration, conservation, and management of mangroves.

15.2 Biodiversity

Owing to their unique and dynamic features, mangrove ecosystems are rich in biodiversity. The mangrove flora consists of ferns, herbs, palms, climbers, shrubs, and trees. Shin et al. (2015) compiled a guidebook to mangrove plants in Malaysia and identified 39 true mangroves and 65 mangrove associates. Table 15.3 shows classification of mangroves in Malaysia based on inundation classes (Watson 1928). Mangrove forest types in Malaysia are also classified according to their location and species dominance (Chan et al. 1993). They include the seaward *Avicennia*-

Table 15.3 Inundation classes of mangroves in Malaysia

Class	Tidal	Elevation (m)	Flooding (times per month)	Vegetation type (dominant species)
I	All high tides	<2.4	56–62	*Rhizophora mucronata*, *Avicennia*, and *Sonneratia*
II	Medium high tides	2.4–3.4	45–59	*Rhizophora*, *Avicennia*, and *Sonneratia*
III	Normal high tides	3.4–4.0	20–45	*Rhizophora apiculata*, *Xylocarpus*, *Bruguiera*, and *Ceriops tagal*
IV	Spring high tides	4.0–4.6	2–20	*Rhizophora*, *Bruguiera*, *Xylocarpus*, and *Excoecaria agallocha*
V	Equinoctial high tides	>4.6	<2	*Bruguiera*, *Excoecaria agallocha*, *Intsia bijuga*, *Heritiera littoralis*, and *Nypa fruticans*

Sonneratia forest, main mangrove *Rhizophora-Bruguiera* forest, and dryland *Lumnitzera-Xylocarpus* forest. The riparian *Nypa fruticans* forest commonly occurs along the banks of tidal rivers with freshwater influence and can extend several kilometers upstream.

Representing the transition into inland forests, dryland mangroves are found at the landward side of mainland mangroves or in the interior of island mangroves. These mangroves are only inundated by occasional spring tides and are often the most diverse in terms of species. In 9 (50 $\times$ 50 m) plots established in a dryland mangrove at Matang, a total of 2012 stems belonging to 30 species and 40 genera were recorded (Chan 1989). Dominant and widespread species (>100 stems/ha) were *Rhizophora apiculata*, *Heritiera littoralis*, and *Ficus microcarpa*. Common species (50–100 stems/ha) were *Flacourtia jangomas*, *Oncosperma tigillarium*, *Bruguiera gymnorhiza*, and *Teijsmanniodendron hollrungii.*

Many species of fauna live in Malaysia's mangroves (Berry 1972; Macnae 1968). The fauna includes invertebrates (mollusks, crustaceans, chelicerates, and insects) and vertebrates (fish, amphibians, reptiles, mammals, and birds). Mangrove forests in East Malaysia are renowned for the iconic proboscis monkey *Nasalis larvatus* (Fig. 15.1). These primates rely on young leaves and immature fruits of mangrove plant species such as *Rhizophora apiculata*, *Rhizophora mucronata*, *Bruguiera parviflora*, *Avicennia alba*, *Sonneratia alba*, and *Sonneratia caseolaris*. Tangah (2012) studied the ecology and behavior of the proboscis monkeys at Labuk Bay in Sabah from 2008 to 2009 (Case Study 15.1). The silver leaf monkey and the long-tailed macaque also live permanently in the mangrove forest feeding on leaves and fruits. Orangutans also frequently prefer mangrove forests to look for their food, especially the fruit of *Ficus microcarpa*.

Fig. 15.1 An adult male proboscis monkey in Labuk Bay, Sabah

Case Study 15.1 Proboscis Monkeys of Labuk Bay, Sabah

The proboscis monkey (*Nasalis larvatus*) is endemic to the island of Borneo. In Sabah, these iconic primates are protected by law throughout their range and are included in Appendix 1 of the CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora), prohibiting all kinds of commercial trade at national and international level. The most recent estimate on the population of proboscis monkeys in Sabah is 6000 (Sha et al. 2008).

In Labuk Bay (236 ha), the total population of proboscis monkeys is 148 individuals (Tangah and Bernard 2010; Tangah 2012). The population increased from two groups when the project was initiated in 2000 to eight groups in 2010. The mangrove forests in Labuk Bay present an interesting case study where proboscis monkeys have become habituated with humans especially for ecotourism purposes. They are provided daily with supplementary food (e.g., cucumbers and pancakes made of corn flour) apart from young leaves and immature fruits from the natural mangrove vegetation such as *Rhizophora apiculata*, *Bruguiera parviflora*, and *Avicennia alba*.

The study at Labuk Bay was aimed at determining the social behavior, aggressive behavior, feeding ecology, sexual behavior, and ranging behavior

(continued)

Case Study 15.1 (continued)
of proboscis monkeys under semi-wild conditions (Tangah 2012). Intensive field data collection, carried out over a period of 12 months (August 2008 to July 2009), involved following monkey groups and observing their behavior from dawn to dusk. Seven proboscis monkey groups, that is, five one-male units and two all-male units, were monitored. Out of the 148 individuals, 34 were adult males, 60 adult females, 33 juveniles, and 21 infants.

The most frequent behavioral activity recorded was resting (32.6%), followed by moving (18.7%), feeding (16.4%), and grooming (13.1%). These results indicated that the activity patterns for semi-wild proboscis monkeys are similar with those in the wild. The number of food plant species consumed by the proboscis monkeys in Labuk Bay was generally low (8–10 species). *Rhizophora apiculata* and *Bruguiera parviflora* were the two most dominant mangrove tree species. Young leaves (62.5%) were the major plant parts consumed followed by immature flowers (5.11%) and young fruits (4.38%). However, the proboscis monkeys also spent ~27% of their time, feeding on supplemented pancakes. An individual consumed 130–300 g of pancakes per day, the major food source. Correlation between pancake consumption and feeding of young leaves showed that they are both equally important food sources. The mean daily ranging distance for the population was 850 m. The shortest daily path length recorded was 335 m. The core ranging areas of the proboscis monkey groups concentrated only within the immediate areas around the feeding platforms in the mangrove forest. The estimated home range of proboscis monkeys was 2–9 ha. This indicates that the small patch of mangrove forest at Labuk Bay (236 ha) may be able to sustain the population of proboscis monkeys. The continued existence of the habituated proboscis monkeys in Labuk Bay may also depend on the availability of supplemented food.

Many species of insects and other arthropods also dwell in the canopy of mangrove trees (Murphy 1990). Reptiles such as monitor lizards, several species of snakes, and small lizards are common. The mangrove intertidal fauna dominated by gastropods and brachyuran crabs has been well documented (Berry 1972; Sasekumar 1974, 1984; Macintosh 1984, 1988; Ashton 1999; Ashton et al. 2003) although a new genus and species of crab was identified in 2015 (Case Study 15.2). Mangrove meiofauna consist predominantly of free-living nematodes, harpacticoid copepods, and kinorhynchs (Sasekumar 1984; Somerfield et al. 1998). The aquatic mangrove fauna in the estuaries, creeks, and inlets is also diverse with fish and shellfish (Khoo 1989, 1990; Chong et al. 1990) which support the livelihoods of coastal communities.

Case Study 15.2 New Genus and Species of Mangrove Crab
Field surveys of crustaceans were conducted in Sabah at Sepilok Laut VJR (28 February to 3 March 2014) and at Lower Kinabatangan-Segama Wetlands (16–21 June 2014) under a collaboration with the Sabah Forestry Department (SFD) and the Tropical Biosphere Research Centre (TBRC), University of Ryukyus, Okinawa, Japan (Tangah et al. 2015). A remarkable scientific achievement was the discovery of a new genus and species of crab named *Exagorium fidelisi* Naruse, AY Chung and Tangah (Naruse et al. 2015; Tangah et al. 2020a). *Exagorium*, the genus name, is derived from the hexagonal shape of the carapace (Fig. 15.2). The species was named after Mr. Fidelis Edwin Bajau, the former Deputy Director of Development, SFD. Belonging to the family Camptandriidae, *Exagorium fidelisi* was sampled from a creek (Sungai Kulamba) adjacent to a *Nypa* forest in Lower Kinabatangan-Segama.

Many species of birds, including migrant birds, feed on the mudflats and roost in the mangrove canopy (Nisbet 1968). The avifauna of Malaysia include a total of 834 species, of which 125 are found within mangrove forests. Out of these, only four species of birds are considered true mangrove specialists, that is, the brown-winged kingfisher (*Pelargopsis amauroptera*), mangrove pitta (*Pitta megarhyncha*), great tit (*Parus major*), and mangrove blue flycatcher (*Cyornis rufigastra*). Despite the limited number of mangrove bird specialists, the mangrove mudflats remain important breeding and foraging habitats to other bird species such as herons and egrets. Mangrove forests are also important as flyway routes for migratory birds. Hence, avifauna diversity can be used as one of the indicators to mangrove forests' eco-health. The avifauna of mangrove forests is listed in Table 15.4. Mangrove bird communities can differ in species richness in relation to localities and floristic diversity of mangrove plants. They utilize mangrove habitat as shelter, feeding, roosting, and breeding grounds. Mangrove birds can be classified into functional

Fig. 15.2 *Exagorium fidelisi*, a new genus and species of crab of the family Camptandriidae in Sabah

Table 15.4 Summary of avifauna in mangrove forests of Malaysia (See et al. 2020)

No	Species (common name)	IUCN status	Description
1	*Pelargopsis amauroptera* (brown-winged kingfisher)[a]	NT	Depends exclusively on mangroves
2	*Halcyon coromanda* (ruddy kingfisher)	LC	
3	*Chrysocolaptes lucidus* (greater flameback)	LC	
4	*Pitta megarhyncha* (mangrove pitta)[a]	NT	
5	*Oriolus xanthornus* (black-hooded oriole)	LC	
6	*Parus major* (great tit)[a]	LC	
7	*Phylloscopus fuscatus* (dusky warbler)	LC	
8	*Cyornis rufigastra* (mangrove blue flycatcher)[a]	LC	
9	*Leptocoma calcostetha* (copper-throated sunbird)	LC	
10	*Pachycephala grisola* (mangrove whistler)	NT	
11	*Ardea sumatrana* (great-billed heron)	LC	Depends exclusively on mangroves for nesting
12	*Ardea alba* (great egret)	LC	
13	*Mycteria cinerea* (milky stork)	EN	
14	*Egretta garzetta* (little egret)	LC	Migrants which depend on mangroves for roosting
15	*Egretta eulophotes* (Chinese egret)	VU	
16	*Ardea intermedia* (intermediate egret)	LC	
17	*Charadrius mongolus* (lesser sand plover)	LC	
18	*Numenius phaeopus* (whimbrel)	LC	
19	*Limosa limosa* (black-tailed godwit)	NT	
20	*Tringa tetanus* (common redshank)	LC	
21	*Tringa terek* (terek sandpiper)	LC	

[a] True mangrove specialist, EN, endangered; VU, vulnerable; NT, near threatened, LC, least concern

groups such as omnivores, frugivores, piscivores, granivores, and migrants (including crustacevores, vermivores, and molluscivores).

15.3 Livelihoods

Coastal communities benefit from mangroves with rich biodiversity to sustain their livelihoods (Spalding et al. 2010). Fish and crustaceans are crucial to coastal livelihoods for essential protein and for trading. The high productivity of mangroves and their capability to support a surplus in fisheries and forest products have contributed to the economic development of the nation. Eighty percent of fishery-related activities occur in the coastal wetlands of Malaysia, which include the mangroves (Sundari et al. 2002). Mangroves are rich feeding and nurturing grounds for many commercial fish species (Sasekumar et al. 1992). The mudflats that occur at the foreshore of mangroves are the habitat for many invertebrates and are used extensively for the culture of the blood cockle *Anadara granosa*.

The selling of forest products also provides important household income, for example, indigenous handicrafts (Case Study 15.3 and Fig. 15.3) and ecotourism in mangroves are also becoming increasingly important in Malaysia. For example, the coastal mangroves of Kuala Selangor help to generate significant revenue from tourists. Visitors go to Kuala Selangor to see the birds, flora and fauna at the Nature Park, and uniquely synchronously flashing fireflies and sample the wide and abundant seafood caught in the area available at the local restaurants and hotels in the area. There has been a long history of mangrove forest management in Malaysia. Traditionally, mangroves have been harvested for fuelwood, charcoal, and poles (Watson 1928; Noakes 1952). The production of charcoal from mangrove wood is

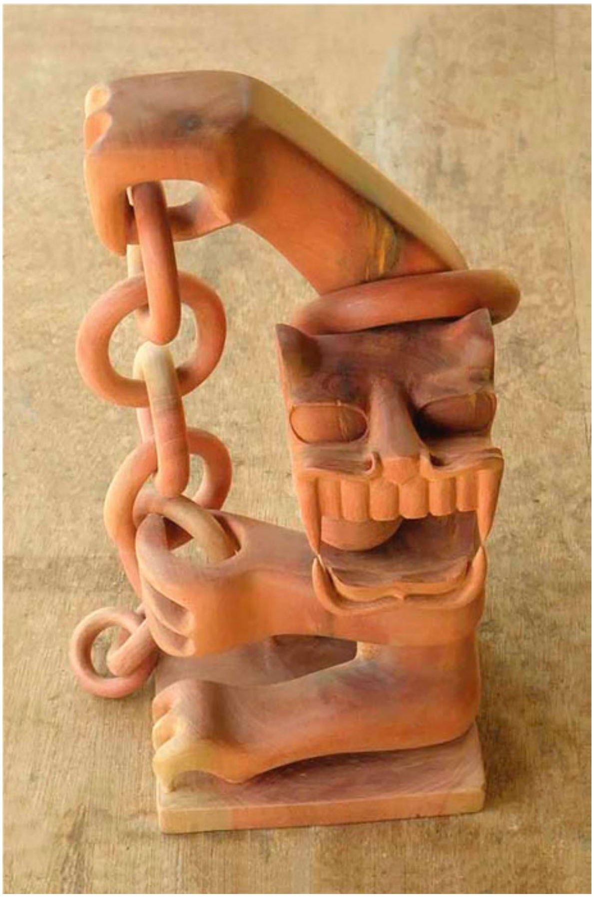

Fig. 15.3 A spiritual figurine carved from the wood of *Xylocarpus* by the Mah Meri tribe

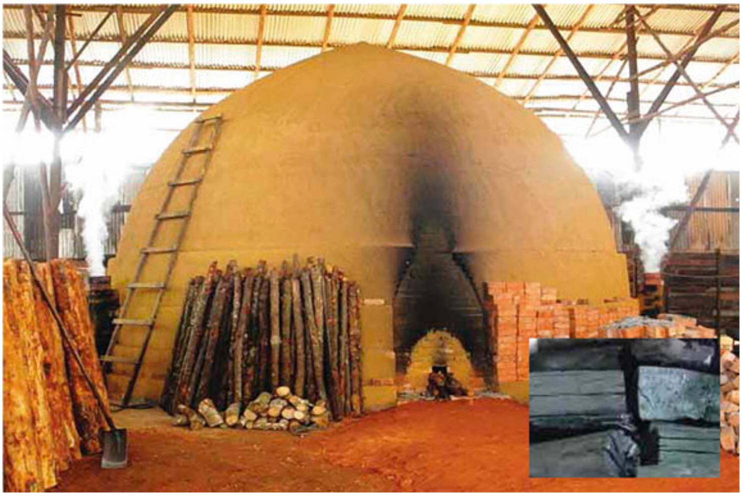

Fig. 15.4 A charcoal kiln in Matang with white smoke emitting from the vents and export-grade charcoal (inset)

still an important forestry industry in Malaysia, especially the Matang mangrove forest which has been managed sustainably on a 30-year rotation for over 100 years (Noakes 1952; Goessens et al. 2014) (Case Study 15.4 and Fig. 15.4). A by-product of the charcoal process wood vinegar has recently become important (Case Study 15.5) and gives added economic and social value to the local communities.

Case Study 15.3 Mangrove Wood Carving by the Mah Meri Tribe
On Carey Island in Selangor, Peninsular Malaysia, the Mah Meri people are an aboriginal community that is rich in culture and tradition (Baba et al. 2013). Residents of the village of Sungai Bumbun, with 500 residents, are well known for their indigenous handicrafts. The women weave exquisite products such as mats, purses, and pouches, while the men carve unique wooden sculptures that have won international awards. Sculptures are often spiritual figurines that are mystical and hauntingly beautiful carved from the wood of *Xylocarpus* (Fig. 15.3). Its wood is favored because of its attractive color and fine texture that contributes to the smoothness of the finished product.

Case Study 15.4 Charcoal Production in Matang, Peninsular Malaysia
In Matang, Peninsular Malaysia, the production of charcoal from *Rhizophora* wood remains the most important forest industry (Amir 2005). There are at present 86 registered charcoal contractors and 348 kilns in operation. In 2012,

(continued)

Case Study 15.4 (continued)

new licenses have been issued to 19 contractors to operate another 140 kilns. *Rhizophora apiculata* and *Rhizophora mucronata* are the two species used for charcoal production. Charcoal factories in Matang are usually constructed close to rivers or canals where transport boats can dock (Chan and Salleh 1987). The factories are made of sawn timber, mangrove poles, and *Nypa* thatches, and they each house a row of 10–12 kilns. The type of charcoal kiln presently used is the Siamese beehive kiln, which was first introduced to Matang in 1930 by charcoal manufacturers from Southern Thailand.

The kiln, a dome-shaped structure resembling an igloo (Fig. 15.4), is made of bricks, sand, and clay (Chan and Salleh 1987; Baba et al. 2013). There are four equidistant smoke vents in the vertical wall, and there is a door, which enables access to the kiln. Costing USD 5000–6000 to construct, the average life of a kiln is about 7–10 years, if constructed on firm ground and regularly used. Each kiln measures 6.7 m in diameter and 7.1 m in height. Each burn requires a charge of 40 tons of greenwood, yielding 10 tons of charcoal. Kilns are normally operational nine times a year, each requiring timber from 2.8 ha of forest.

On arrival of the boat, mangrove billets are unloaded and stacked outside the factory (Chan and Salleh 1987; Baba et al. 2013). If debarking is not done in the forest, charcoal producers would employ workers to debark the billets, as debarked wood gives better charcoal yield. After debarking, the billets are shoulder carried into the kiln and filled by vertical close-packing. The bottom ends of each billet are placed over with a piece of brick to ensure complete carbonization at the ground level. Only the base of the kiln is packed, leaving the upper portion of the dome empty. When the kiln is loaded, the entrance door is sealed to form a firing port at the bottom. Normally, small-diameter mangrove billets (less than 10 cm) are used for firing. Due to the increasing difficulty in obtaining adequate supply, some operators have started to use rubber wood or timber offcuts, purchased from nearby sawmills. The firing schedule involves three stages (Loo et al. 2008). Stage I is the burning of billets at 100–120 °C for 8–10 days. Stage II is characterized by a higher temperature of 250 °C. At this stage, the kiln entrance is partially sealed, preventing complete combustion of wood. This carbonization stage takes about 12–14 days. During Stage III, the charcoal is left to cool for 8–9 days. The kiln entrance and smoke vents are completely sealed at this stage. The whole process of charcoal production takes about 28–30 days. The timing of each stage is determined by a headman who is guided by the color and odor of the smoke emitted from the vents.

The present market value of high-grade charcoal (Fig. 15.4 inset) is about USD 200 per ton (Baba et al. 2013). Some 30% of the charcoal produced from Matang is exported to Japan. Two local incorporated Japanese companies are involved in purchasing, grading, and packing the charcoal for export to Japan.

(continued)

Case Study 15.4 (continued)
Charcoal from Matang has set an international benchmark for quality and attracts premium prices. The Matang charcoal is smokeless and burns three times longer. In Japanese homes, the high-grade charcoal is used for barbecuing and tea making and as natural deodorizer and water purifier.

Case Study 15.5 Wood Vinegar Production in Matang, Peninsular Malaysia
In recent years, charcoal operators in Matang have started to produce wood vinegar as a by-product of charcoal making (Loo et al. 2008; Baba et al. 2013). The by-product collected as raw distillate is pyroligneous acid. Smoke from the vents of the charcoal kiln is condensed and collected using a network of stainless steel tubes and funnels as condensers. Mangrove wood vinegar is collected at Stage II of the firing schedule when the entrance of the kiln is partially sealed to prevent complete combustion. During this stage of charcoal production (12–14 days in duration), the temperature inside the kiln reaches 250 °C, and smoke emerging from the vents of the kiln is about 50–70 °C. The smoke, collected using a stainless steel cone, is channeled through a steel pipe where it condenses and the wood vinegar flows back into a drum. Freshly collected wood vinegar has a temperature of 36–38 °C and a smoky odor. The condensate when fractionated yields 5.5% acetic acid, 3.4% methanol, and 6.5% wood tar. Due to its high content of volatile acids (8–10%), wood vinegar is acidic (pH 2–3) and mildly corrosive.

Before distillation, wood vinegar is almost black in color, resembling coffee (Chan et al. 2012a, b). After distillation, it becomes a golden-brown liquid, resembling tea. Extracts of wood vinegar from Matang have been studied for its phenolic content and antioxidant properties, with the isolation of three chemical compounds (Loo et al. 2008). Antioxidant properties of the wood vinegar (non-distilled) were stronger than or comparable with those of black tea (*Camellia sinensis*) (Chan et al. 2012a). Potent and broad-spectrum antibacterial activity of the mangrove wood vinegar has also been reported (Chan et al. 2012b). Both the distilled and non-distilled wood vinegar at 50% concentration inhibited all three gram-positive and all three gram-negative bacteria tested.

Wood vinegar has been traditionally used as sterilizer, deodorizer, and fertilizer and as antimicrobial and growth-promoting agent (Loo et al. 2008). It has a wide range of industrial, agricultural, medicinal, and home applications. In Thailand, wood vinegar is used to treat skin infections and dandruff.

15.4 Threats

Malaysia's land use policy is "use-oriented," that is, formulated for maximum exploitation and development (MoSTE 1997). Thus, conversion of land for urbanization, industrial, agricultural, mining, and forestry development has higher priority than that of conservation, although it is probable that conservation for sustainable resource use has a higher rate of return on investment in the long term in the form of payments for ecosystem services (PES). This is because, when decisions are made on the conversion of mangroves to other land uses, the cost/benefit analyses used in these situations often do not take into account the full range of benefits of the mangrove area to be converted (Sundari et al. 2002). The value of mangroves in providing various environmental and cultural services has rarely been considered in decision-making.

The Land Capability Classification (LCC) which is applicable throughout Malaysia divides land use into five categories, mining, agriculture covering a wide range of possible crops, agriculture for a restricted range of possible crops, forestry, and conservation, based on potential productivity and economic yield of the land in question. Land designated for conservation has the lowest priority in this order (MoSTE 1997). Since its implementation, the LCC has introduced major land use changes which have been financially beneficial and have done much to address problems of rural poverty and social inequality. The weakness of LCC is its limited applicability to adequately addressing biological diversity and conservation issues, although conservation has been widely defined as the judicious use and management of nature and natural resources for the benefit of human society and ethical reasons. Development projects in mangrove areas (whether planned or unplanned) compromise the ecological integrity of intact mangrove areas and result in loss or degradation of these sensitive yet fragile ecosystems.

The threats to mangroves in Malaysia have been emphasized by Latiff and Faridah-Hanum (2014) for Malaysia and by Tangah et al. (2020b) for Sabah. The major threats are listed in Table 15.5. It is undeniable that agricultural commodities have brought prosperity and economic development in Malaysia. The oil palm industry generates incomes for major companies and smallholders alike, reducing poverty and increasing the chances of local communities to enjoy higher quality of life such as better infrastructures, access roads, and better opportunity to education

Table 15.5 Major threats to mangrove forests in Malaysia

No	Threats	Description
1	Mangrove conversion	Mangroves are cleared and reclaimed or drained with embankments for commercial crops especially oil palm plantations
2	Bark smuggling	Illegal smuggling of *Ceriops tagal* (tengar) bark for tannin, cloth dye, and beverage flavoring
3	Aquaculture development	Clearance of mangroves for aquaculture and related development
4	Human settlements	Mangrove clearance for housing/settlements, including access roads and modified landscape to allow cultivation of crops

and healthcare. However, the oil palm industry is land use intensive, and the mindset is still bigger land, bigger returns. In the past decades, Malaysia's mangroves had been ravaged in an attempt to increase plantation area.

15.5 Restoration, Conservation, and Management

The Sabah Forestry Department (SFD) and the International Society of Mangrove Ecosystems (ISME) collaborative project to rehabilitate degraded mangroves in Sabah was initiated in 2011 (Tangah et al. 2015). Funded by Tokio Marine and Nichido Fire Insurance Co., Ltd., the mangrove restoration project was implemented by SFD with technical guidance from ISME. Two major studies implemented under the project were in Sungai ISME and in Sungai Tokio Marine (Tangah et al. 2020a). In 2017, SFD established a long-term ecological research site at Sepilok Laut to better understand the ecological aspects of natural mangrove ecosystems. In 2019, a simple performance evaluation of three mangrove rehabilitation projects implemented by ISME was undertaken (Baba et al. 2019).

15.5.1 Sungai ISME

In 2011, the rehabilitation of a degraded mangrove forest at Sungai ISME (2 ha) was initiated. The study was declared a success and fully regenerated in 2020 (Tangah et al. 2020a). Six species planted were *Avicennia alba*, *Bruguiera cylindrica*, *Ceriops tagal*, *Rhizophora apiculata*, *Rhizophora mucronata*, and *Terminalia catappa* (Table 15.6). An assessment of plants conducted 4 years after planting revealed the presence of 16 mangroves species belonging to 6 families and another 36 coastal species belonging to 21 families (Tables 15.6 and 15.7). Two individuals of *Sonneratia* x *hainanensis*, a natural hybrid of *Sonneratia alba* (maternal parent) and *Sonneratia ovata* (paternal parent), were encountered. Trees of *S. alba* occur within the project site while several individuals of *Sonneratia ovata* were observed along the river of Sungai ISME at the eastern boundary of the project site. A survey mapped the locations of the major plant species and their heights in relation to their ground level and flooding frequency. From the results, it is possible to determine the ecological niches of each species by interpreting their site preferences and physiological tolerance. The most suitable habitats for planting *Rhizophora apiculata* and *Rhizophora mucronata* are the intertidal beds and slopes of channels. Planting sites of *Terminalia catappa* are the bund tops.

Overall, the survival rate of planted mangroves in Sungai ISME is above 80% and further replanting is not necessary. Species with outstanding growth rates at Sungai ISME are *Avicennia alba*, *Terminalia catappa*, *Rhizophora mucronata*, and *Rhizophora apiculata*. This suggests that propagules of *Rhizophora apiculata* and *Rhizophora mucronata* are the best choices of planting materials in degraded mangrove habitat whereas seedlings of *Terminalia catappa* are the best choice for

Table 15.6 Planted and wild mangrove plant species found at Sungai ISME in 2016

No	Mangrove plant species	No	Mangrove plant species
1	*Avicennia alba*[a]	9	*Lumnitzera racemosa*
2	*Acrostichum aureum*	10	*Lumnitzera littorea*
3	*Bruguiera parviflora*	11	*Nypa fruticans*
4	*Bruguiera cylindrica*[a]	12	*Rhizophora mucronata*[a]
5	*Bruguiera sexangula*	13	*Rhizophora apiculata*[a]
6	*Ceriops tagal*[a]	14	*Sonneratia alba*
7	*Ceriops zippeliana*	15	*Sonneratia* x *hainanensis*[b]
8	*Excoecaria agallocha*	16	*Xylocarpus granatum*

[a] Mangrove species planted in 2011
[b] A hybrid of *Sonneratia alba* and *Sonneratia ovata*

Table 15.7 Coastal plant species found at the planting site of Sungai ISME in 2016

No	Coastal plant species	No	Coastal plant species
1	*Acacia mangium*	19	*Ischaemum muticum*
2	*Allophylus cobbe*	20	*Imperata confertum*
3	*Benincasa hispida*	21	*Lygodium microphyllum*
4	*Calamus erinaceus*	22	*Melastoma malabathricum*
5	*Carex indica*	23	*Microsorum scolopendrium*
6	*Chloris barbata*	24	*Morinda citrifolia*
7	*Cyperus diffusus*	25	*Nephrolepis biserrata*
8	*Dalbergia candenatensis*	26	*Oxyceros longiflora*
9	*Derris trifoliata*	27	*Passiflora foetida*
10	*Eclipta erecta*	28	*Pluchea indica*
11	*Eupatorium odoratum*	29	*Phyllanthus urinaria*
12	*Flagellaria indica*	30	*Pongamia pinnata*
13	*Ficus microcarpa*	31	*Sida rhombifolia*
14	*Glochidion littorale*	32	*Sida elliptica*
15	*Heritiera littoralis*	33	*Sporobolus indicus*
16	*Talipariti tiliaceum*	34	*Stenochlaena palustris*
17	*Hyptis* sp.	35	*Terminalia catappa*[a]
18	*Ischaemum magnum*	36	*Vitex pinnata*

[a] The only coastal species planted in 2011

planting on bund tops in Sungai ISME and may also be applied to other rehabilitation sites in Malaysia.

Insect diversity is often used as bioindicators to indicate the effects of mangrove habitat changes and fragmentation and the effectiveness of management schemes (Chung et al. 2018). Nocturnal insect diversity was monitored through light trapping since 2015. Diurnal insects were sampled using sweep nets and forceps. Insect diversity indices as well as species richness and abundance were used to monitor the environmental status of the mangrove rehabilitation site (Chung and Tangah 2015; Tangah et al. 2020a). The insect data procured from surveys in 2015–2017 serve as baseline information for this area. It can be used to evaluate the status of biodiversity in Sungai ISME for the subsequent years. There is an improvement in insect fauna population, but diversity is still low compared to other forested sites in Sabah. From the insect survey of Sungai ISME, there are 14 species of Coleoptera (beetles), 2 species of Diptera (flies), 6 species of Hemiptera (bugs), 8 species of Hymenoptera (ants, bees, and wasps), 48 species of Lepidoptera (20 butterflies and 28 moths), 5 species of Neuroptera (lacewings and ant lions), 9 species of Odonata (dragonflies and damselflies), and 7 species of Orthoptera (grasshoppers and bush crickets). The insect data serve as baseline information for future research work on mangrove rehabilitation as well as to strengthen the ongoing collaborative research among relevant agencies on tropical mangrove ecosystems. Insects are ecologically significant in the mangrove ecosystem as pollinators, defoliators, borers, decomposers, as well as source of food for other animals and will contribute to the success of mangrove rehabilitation. Research activities also serve as a guide to research and development (R&D) plans for mangrove rehabilitation.

In April 2019, a night survey of Sungai ISME was conducted, and an interesting species of frog was encountered (Tangah et al. 2020a). The frog camouflages itself by having a body coloration and patterning that blended with the muddy mangrove substrate. It was identified as *Fejervarya cancrivora* (Fig. 15.5), also known as the nocturnal Asian brackish frog or crab-eating frog. This unique crab-eating frog in the mangroves was named as *Rana cancrivora* by Macnae (1968).

15.5.2 Sungai Tokio Marine

At Sungai Tokio Marine, an illegal shrimp farm comprising 13 ponds of 56 ha encroached into the Kuala Tingkayu MFR. Planting in the confiscated pond sites was conducted from 2014 to 2017. A total of 156,000 propagules, seeds, and seedlings of *Avicennia alba*, *Nypa fruticans*, *Rhizophora apiculata*, *Rhizophora mucronata*, and

Fig. 15.5 *Fejervarya cancrivora*

Fig. 15.6 Migratory egrets are waiting for the pond water to recede at Sungai Tokio Marine

Terminalia catappa were planted (Tangah et al. 2020a). The early phases of planting in the ponds (2014–2015) were most challenging. High mortality rates were encountered due to acid sulfate soils and poor drainage. Planted *Rhizophora* propagules had their embedded parts darkened and failed to produce roots and establish. Planting became more successful after several years of tidal flushing by breaching the pond bunds to facilitate water inflow and outflow. Progressively, *Rhizophora mucronata* established well along the perimeter of ponds with higher ground elevation. Growth of *Rhizophora* in the lower sections of the pond substrate was less luxuriant and less dense. Planting of *Terminalia catappa* on the top of bunds was the most successful with some trees producing seedlings beneath them. Besides improving tidal flow and drainage, and reducing the problem of acid sulfate soils, the breaching of the bunds would encourage the inflow of waterborne propagules from the adjacent forest into the ponds. The newly established mangrove plantations in the ponds at Sungai Tokio Marine have attracted flocks of migratory egrets (Fig. 15.6).

15.5.3 Sepilok Laut

To monitor the long-term health of mangroves (e.g., from changes in growth rates and demographic shifts) as well as to gain a better understanding of various ecological aspects of mangrove ecosystems, SFD established a long-term ecological research site at Sepilok Laut in Sabah in 2017 (Tangah et al. 2018) (Case Study 15.6 and Fig. 15.7).

Case Study 15.6 Long-Term Ecological Research at Sepilok Laut, Sabah
Five permanent circular plots, 15 m in radius or 0.7 ha in area, were set up linearly, 50–80 m apart and ~10 m along the boardwalk that connects to the Sepilok Laut Reception Centre VJR. The plots are advocated as an approach that is robust in documenting detailed changes in forest structure and composition. They also provide baseline distribution data for species and provide information on the habitats. Continuous long-term monitoring of these plots will provide valuable information on changes in plant diversity, richness,

(continued)

Case Study 15.6 (continued)
growth, mortality, regeneration, and dynamics of the sampled mangrove forest. The measurement of all trees above 10 cm dbh and height of all trees above 20 cm were taken. Trees were marked with red paint and tagged and their diameters measured (Fig. 15.6). A total of 218 individual trees from 233 stems were recorded. They represent the intermediate, back, and riparian mangrove zones.

Data collection was conducted yearly in 2017, 2018, and 2019. There was no measurement taken in 2020 due to the global pandemic of COVID-19. From 2021, measurements will be carried out once every three years. The 2017 data showed distinct species composition in relation to plot location in the different mangrove zones. Plot 1 (being the most seaward) is in the main mangrove zone while Plot 5 (being the most landward) is in the back mangrove zone. Plot 1 contained *Ceriops tagal* (36), *Rhizophora apiculata* (9), *Lumnitzera littorea* (8), and *Scyphiphora hydrophylacea* (1) that were not found in Plot 5. *Syzygium leucoxylon* (13), *Heritiera littoralis* (9), *Pouteria obovata* (5), and *Diospyros ferrea* (1) were found in Plot 5 but not in Plot 1.

15.5.3.1 Mangrove Rehabilitation Projects Implemented by ISME

In 2019, a comparative study was carried out on three mangrove rehabilitation projects at Kiribati, Gujarat, and Sabah (Baba et al. 2019). Implemented by ISME, the objectives, forestry approaches, habitats, choice of species, planting techniques,

Fig. 15.7 Marking trees with red paint (left) before tagging and measuring their diameters (right) at LTER, Sepilok Laut, Sabah

and implementation of the three projects are shown below. Based on ten criteria (accessibility, collaboration, objectives, costs, publicity, capacity building, voluntary participation, community participation, conservation awareness, and sustainability), a simple performance evaluation of the projects was conducted, and results are shown in Table 15.8.

Tarawa, Kiribati, mangrove rehabilitation since 2004.

Objectives: To establish mangrove vegetation on low-lying atolls in anticipation of problems associated with climate change, that is, sea level rise, storm damage, and coastal erosion.
Forestry approach: Afforestation.
Habitat: Nutrient poor and hypersaline white coral sand flats with little freshwater inputs from the rain.
Choice of species: Rhizophora stylosa.
Planting technique: Close group planting of propagules.
Implementation: Planting by school children and youth.

Gujarat, India, mangrove plantations since 2009.

Objectives: To establish mangrove plantations for coastal protection, to create habitats for endangered birds, and to generate income for the local community.
Forestry approach: Afforestation.
Habitat: Barren mudflats with strong tidal current during the high tide.
Choice of species: *Avicennia marina.*
Planting technique: Line planting of propagules and replanting with nursery raised seedlings.
Implementation: Planting and nursery work by womenfolk from nearby villages, supervised by Daheda Sangh, a local NGO.

Sabah, Malaysia, rehabilitation of degraded mangroves since 2011.

Objectives: To rehabilitate mangrove forests encroached illegally by oil palm plantations and shrimp ponds and to enhance ecosystem recovery.

Table 15.8 Performance evaluation of ISME mangrove rehabilitation projects (Baba et al. 2019)

Evaluation criteria	Tarawa, Kiribati	Gujarat, India	Sabah, Malaysia
Accessibility	+	++	+++
Collaboration	++	++	+++
Objectives	+++	+++	+++
Costs	++	+++	+
Publicity	++	+	+++
Capacity building	++	+	+++
Voluntary participation	++	+	+++
Community participation	++	+++	+
Conservation awareness	++	++	++
Sustainability	++	+	+++
Overall performance	20	19	25

Forestry approach: Reforestation.
Habitats: Cleared and bunded degraded mangrove sites.
Choice of species: Rhizophora in tidal sites, *Terminalia catappa* on bund tops, and *Rhizophora* and *Nypa* in abandoned shrimp ponds.
Planting techniques: Line, random, and cluster planting of propagules, seeds, seedlings, and stem cuttings.
Implementation: Planting by contractors, supervised by the mangrove team of SFD.

From the project performance, Tawara scores moderately in all criteria, except for accessibility due to its remoteness in the Pacific and difficulty in interisland travel. Gujarat scores strongly in community participation and project costs but weakly in publicity, capacity building, and sustainability. It is very unlikely that the local NGO will be able to sustain the project after ISME. Sabah scores strongly in accessibility, collaboration, publicity, capacity building, voluntary participation, and sustainability but weak in community participation and project costs. However, a substantial part of the project costs such as salaries, subsistence, and transportation of project personnel are borne by SFD. Other distinguishing features of the rehabilitation project in Sabah are the different habitats and species planted, the different planting techniques employed, full-time staff and logistics provided by SFD, and employment of planting contractors supervised by SFD.

15.6 Conclusions

Under the management of mangroves in Malaysia, gazettement of all mangroves in the states as forest reserves is an ideal proposal. However, this is not entirely possible. Some mangrove areas have to be designated as conservation areas for protection of the environment including biodiversity. Remaining areas are classified as state land that are available for development involving conversion to other land uses. Forest reserves come under the jurisdiction of the forestry departments. Conservation areas in the form of wildlife sanctuaries, state parks, and marine parks are managed by the wildlife and related departments. Such legislative and management framework operating at the national and state levels inevitably results in the overlapping of jurisdiction and/or conflicts in decision-making with regard to mangrove resources. There is therefore a need for Malaysia to have a policy of integrated coastal management that ensures the sustainability of mangrove ecosystems and their ecological services. The development of a mangrove action plan (MAP) is a step in the right direction. In MAP, decision-making among the different stakeholders will have to address the following issues:

- Identifying and overcoming the threats to sustainable development planning.
- Strengthening the environmental sustainability of coastal development.
- Promoting sound investments in coastal ecosystem management as a means of enhancing resilience and supporting local livelihoods.

- Enhancing the participation of local communities in the implementation of management activities.
- Collaborating with scientists from international organizations, for example, ISME and TBRC would benefit SFD in improving mangrove R&D.

A crucial element is the assessment of climate vulnerability and climate adaptation recommendations for the Malaysian coastal area. As sea level rises due to climate change, a significant percentage of low-lying coastal areas in Malaysia will be under seawater, displacing the settlements and livelihoods of local communities. When more mangrove areas are submerged in water, there will be increasing pressures for establishing new areas for community resettlements. As this happens, inland mangrove areas could be the nearest option. The establishment of MAP is crucial and will involve extensive multi-stakeholder's consultation at the state and national levels. Priority actions will be identified with desired outcomes anticipated, time frames defined, and performance indicators outlined. MAP will rely on and conform with existing laws and policies related to mangroves and other coastal ecosystems. The overall goal will benefit the people and mangrove ecosystems.

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Chapter 16
Mangrove Biodiversity, Conservation and Roles for Livelihoods in Indonesia

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Abstract Indonesia is an archipelagic nation that comprises more than 17,504 islands and hosts the largest mangrove forest area in the world, consisting of 2.7 million ha in 2020. Mangrove forests in Indonesia distribute across all 34 provinces, with major areas distributed in the Eastern Indonesia region. Papua province has the largest mangrove area with 26.6% and followed by West Papua (17.5%), East Kalimantan (7.5%) and North Kalimantan (5.6%). Mangroves in deltaic and estuary settings in Indonesia are developed in a relatively large area in major islands, while

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oceanic mangroves typically occur across small islands, particularly in Sulawesi and Maluku regions. Mangrove flora in Indonesia comprises 157 species, of which 52 tree species (true mangrove), 21 species of shrubs, 13 species of liana, 7 species of palms, 14 species of grasses, 8 species of herbs, 3 species of parasites, 36 species of epiphytes and 3 species of ferns. There are approximately 122 species of invertebrates, 45 species of fishes and 148 species of terrestrial fauna found in Indonesian mangroves. Mangroves in Indonesia have faced direct human-made threats including deforestation and forest conversion to other land uses. Despite facing anthropogenic and non-anthropogenic disturbances, mangroves provide great benefits and support livelihoods to millions of coastal communities in Indonesia. On the other hand, maintaining natural and important mangrove functions in contributing to climate change mitigation and coastal adaptation.

Keywords Indonesia · Mangrove · Biodiversity · Restoration · Livelihood · Ecosystem service

16.1 Introduction

Indonesia is an archipelagic nation that comprises more than 17,504 islands and hosts the largest mangrove forest area in the world, consisting of 2.7 million ha in 2020 (Fig. 16.1). Despite only occupying 1.3% of the earth's surface area, mangrove ecosystems across the world are home to 10% of the flowering plants, 12% of the mammals, 16% of the reptiles and amphibians, 17% of the birds and 35% of the fishes (Tomlinson 2016). Mangrove supports a wide range of ecosystem services (ES) particularly in the coastal and marine habitats, including coral reefs, seagrass beds, mudflats and sand flats (Duke et al. 2014). The large extent of Indonesia's waters within the Indo-West Pacific seas region is further contributing to the country's biodiversity (Cámara-Leret et al. 2020).

The area of Indonesian mangroves has been experiencing a significant decrease over the past five decades (Ilman et al. 2016). The drivers of mangrove degradation and loss in Indonesia are mainly due to anthropogenic factors in the form of land cover changes as well as natural factors such as the 2004 tsunami. Despite facing anthropogenic and non-anthropogenic pressures, mangroves provide great benefits and support livelihoods to millions of coastal communities in Indonesia.

Thus to reverse these losses, mangrove conservation in Indonesia has been long implemented by multiple stakeholders such as government institutions, non-governmental organizations (NGOs), communities and private sectors. As a result, multiple regulations associated with mangrove conservation and management were produced to maintain national mangroves, preserve and protect mangroves from further loss and rehabilitate degraded mangroves to increase national mangrove area.

This chapter describes the current research and updates on biodiversity, livelihood and conservation in the mangrove ecosystem in Indonesia. The national mangrove area and distribution, ecology and biogeography characteristics, floristic

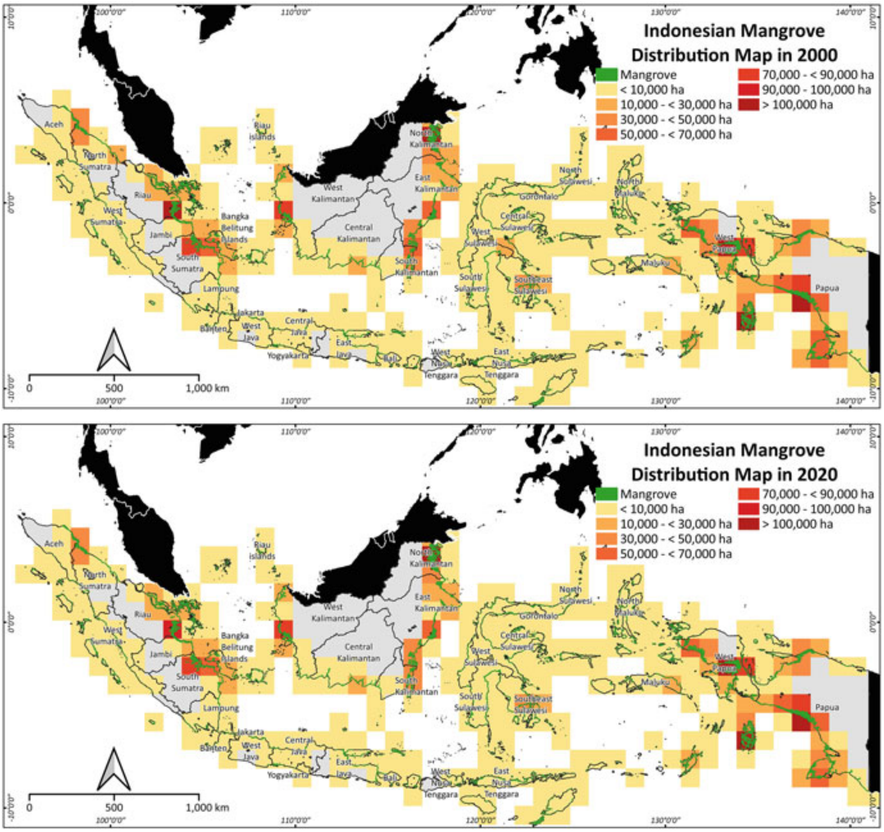

Fig. 16.1 Mangrove distribution in Indonesia (top panel shows mangrove distribution in 2000 and bottom panel shows mangrove distribution in 2020). Data were obtained from Giri (2021) with annual forest cover loss between 2001 and 2020 version 1.8 by Hansen et al. (2013)

composition, aquatic microorganism biodiversity, ecosystem services deliverable for coastal communities and potential impacts from global changes such as anthropogenic disturbance are outlined. Previous examples from Indonesia have shown how a population of 42 million from coastal communities depend on fisheries product (BPS 2020), of which mangrove has a key role to support fisheries and therefore conservation and improved management for this ecosystem is necessary. This chapter provides a successful case study of mangrove rehabilitation and community-based mangrove management and describes how priority research recommendations may be formulated to fill the current knowledge gaps for mangrove conservation in Indonesia.

16.2 Mangrove Area and Distribution

Mangrove forests in Indonesia are distributed across all 34 provinces with major areas in the Eastern Indonesia region (Fig. 16.1). Papua province has the largest mangrove area with 26.6% followed by West Papua (17.5%), East Kalimantan (7.5%) and North Kalimantan (5.6%) (Table 16.1). Overall, the national mangrove

Table 16.1 Distribution and mangrove area in Indonesia between 2000 and 2020

Province	Island	2000	2020	Gap 2000–2020
Bali	Bali Nusa	1834.88	1823.83	11.05
East Nusa Tenggara	Bali Nusa	19,007.60	18,665.03	342.57
West Nusa Tenggara	Bali Nusa	4847.26	4675.28	171.98
Banten	Jawa	2542.73	2406.12	136.61
Central Java	Jawa	10,431.40	10,166.91	264.49
East Java	Jawa	25,873.11	25,630.19	242.93
Jakarta	Jawa	89.91	89.46	65.50
West Java	Jawa	5867.70	5802.20	65.50
Yogyakarta	Jawa	3.36	3.36	0.00
Central Kalimantan	Kalimantan	47,027.12	40,248.50	6778.62
East Kalimantan	Kalimantan	242,670.03	203,105.15	39,564.88
North Kalimantan	Kalimantan	192,192.00	153,240.68	38,951.32
West Kalimantan	Kalimantan	123,564.91	113,271.25	10,293.66
South Kalimantan	Kalimantan	70,806.82	61,180.16	9626.66
Maluku	Maluku	193,599.12	192,203.87	1395.25
North Maluku	Maluku	41,217.75	40,321.17	896.58
Papua	Papua	734,337.27	726,407.79	7929.48
West Papua	Papua	486,563.10	481,480.48	5082.63
Central Sulawesi	Sulawesi	33,230.52	30,196.10	3034.42
Gorontalo	Sulawesi	11,604.67	9420.94	2183.73
North Sulawesi	Sulawesi	11,403.53	11,011.56	391.97
South Sulawesi	Sulawesi	27,111.29	23,449.21	3662.07
Southeast Sulawesi	Sulawesi	67,214.10	61,013.16	6200.94
West Sulawesi	Sulawesi	4910.52	3584.74	1325.78
Aceh	Sumatra	33,142.06	31,321.79	1820.27
Bangka Belitung Island	Sumatra	65,486.96	61,664.34	3822.61
Bengkulu	Sumatra	2065.63	1969.47	96.15
Jambi	Sumatra	4194.57	3843.25	351.32
Lampung	Sumatra	6596.02	5941.21	654.82
North Sumatra	Sumatra	66,873.10	57,010.06	9863.04
Riau	Sumatra	153,722.45	143,596.70	10,125.75
Riau Islands	Sumatra	56,098.22	52,008.02	4090.20
South Sumatra	Sumatra	166,199.91	142,681.40	23,518.50
West Sumatra	Sumatra	18,023.26	17,552.48	470.79
		2,930,352.90	2,736,985.87	193,367.03

area reduced by 7% over the past 20 years, from 2,930,352 ha in 2000 to 2,736,985 ha in 2020, or equal to 0.35% annually. The rates of mangrove loss in Indonesia are similar to the global pattern of mangroves lost between 0.16 and 0.39% globally from 2000 to 2012 (Hamilton and Casey 2016). Current annual mangrove loss rates in Indonesia were substantially lower compared to the previous decades, specifically during the 1980s–2000s when nearly 52,000 ha of mangroves were deforested during those periods (Murdiyarso et al. 2015).

Mangrove deforestation in Indonesia is mostly driven by timber extraction or logging and conversion to other land uses due to the expansion of several commodities including land-based aquaculture, oil palm plantation, coconut plantation as well as non-productive conversion, erosion and settlement (Goldberg et al. 2020; Richards and Friess 2016). Most of these man-made disturbances occurred previously in the Western Indonesia region, including Sumatra and Java and Kalimantan (Table 16.1). Here mangroves were majorly converted into fish and shrimp ponds as part of the aquaculture expansion (Ilman et al. 2016). Until 2018, approximately 650.509 ha of aquaculture ponds were developed and actively operated across coastal areas of Indonesia (MMAF 2018). This number may not include the area of unproductive ponds where many cases were observed in some places including East Kalimantan (Aslan et al. 2021). Moreover, some of the new frontier land uses such as oil palm and coconut plantations were driving mangrove losses in several places of Sumatra (Richards and Friess 2016; Eddy et al. 2021b). While these commodity crops are originally grown in upland mineral soils, it is still unclear how waterlogged coastal habitat may affect their productivity. Therefore, restoring previously degraded and converted mangroves is necessary and may not only reverse the current annual mangrove loss rates but also increase the net mangrove area in Indonesia at a long-term time scale.

16.3 Ecology and Biogeography Characteristics

Mangrove forests in the Indo-Pacific region including Indonesia are characterized by tall tree composition (>20 m) with dominant species of *Rhizophora* spp. (Duke et al. 1998; Simard et al. 2019). Most of these mangroves are commonly located across three major hydrogeomorphic settings such as river delta, estuary and oceanic habitats (Worthington et al. 2020). Mangroves in deltaic and estuary settings in Indonesia are developed in a relatively large area (more than 20,000 ha). For example, these typical mangroves can be observed in Indragiri Hilir, Sembilan, Kubu Raya, Mahakam, North Kalimantan, Bintuni Bay and Mimika. All of these locations are located on major islands where coastal sediment inputs are sustained by sufficient sediment capital located in the upland areas (Fig. 16.2). Moreover, oceanic mangroves typically occur across small islands, particularly in Sulawesi and Maluku regions. They are commonly developed at the steeped shoreline with lower sediment inputs and availability, and therefore their area is considerably smaller compared to

Fig. 16.2 The geographical location of mangrove hydrogeomorphic settings across Indonesia (Worthington et al. 2020)

delta and estuary mangroves (Fig. 16.2). Oceanic mangroves are also associated with other coastal ecosystems such as coral reefs and seagrasses.

Mangrove forests in Indonesia are typically stratified into two classes (i.e. primary and secondary mangroves) depending on the degree of the degradation. Primary mangrove is characterized by tall mangrove trees and a closed canopy with a forest structure by tree density typically between 500 and 1000 trees/ha but with a highly varied basal area ranging from 10 to 75 m^2/ha (Sasmito et al. 2020; Murdiyarso et al. 2021). This low tree density and high basal area are normally observed at areas where coastal habitats are pristine with high domination of large trees, such as in West Papua and Papua provinces (Aslan et al. 2016; Sasmito et al. 2020). By contrast, secondary mangrove forests have experienced some disturbances such as deforestation, conversion and secondary regrowth. Therefore, their forest structure is highly varied depending on the types of disturbances. Deforestation and logging reduce standing tree biomass up to nearly 100% (Sillanpää et al. 2017; Sasmito et al. 2020; Murdiyarso et al. 2021), while regrowth forests at ages between 5 and 15 years are characterized by a highly dense canopy (more than 2000 trees/ha) but with a typically low basal area (1–15 m^2/ha) (Sukardjo et al. 2014; Sidik et al. 2019; Murdiyarso et al. 2021). Moreover, converted mangroves such as aquaculture ponds have a low forest structure depending on the layout of the pond areas where normally mangroves are planted across pond walls to protect from erosion (Arifanti et al. 2019).

Indonesian primary mangroves store a high total biomass (above- and below-ground biomass) with its mean approximately at 400 ton/ha (Murdiyarso et al. 2015). A high biomass value in natural primary forests is reflected by their high basal area despite low tree density compared to secondary forests. The large mangrove biomass is typically observed in estuary mangrove settings where hydrodynamics are controlled by a high tidal range and supported by sustained sediment inputs. Such characteristics are observed in Bintuni Bay, where the largest mangrove block and the tallest mangrove tree in Indonesia are located (Simard et al. 2019). Rates of litter productivity in Indonesian primary mangroves range between 19 and 27 ton/ha/year (Sukardjo et al. 2013) or approximately 2–3 times higher than rates observed in a low land rainforest in Sumatra (8 ton/ha/year, Kotowska et al. (2015)) and tropical peat swamp forest in Kalimantan (9 ton/ha/year, Saragi-Sasmito et al. (2019)). Overall, the high carbon stocks, biomass, forest structure and basal area in Indonesian mangroves could be due to significant inputs of the biomass productivity with substantial carbon-rich sediment inputs across different types of their hydrogeomorphic settings (Rovai et al. 2021).

16.4 Floral and Faunal Biodiversity

16.4.1 Floral Mangroves

The variation of species richness and diversity of mangrove forests is driven by the unique environmental condition of the region. Sandilyan and Kathiresan (2012) described that globally mangroves are composed of 73 species of trees and shrubs. Mangrove flora in Indonesia comprises 157 species, of which 52 tree species (true mangrove), 21 species of shrubs, 13 species of liana, 7 species of palms, 14 species of grasses, 8 species of herbs, 3 species of parasites, 36 species of epiphytes and 3 species of ferns (Soemodihardjo et al. 1993). Moreover, Kusmana (1993) reported approximately 202 mangrove plant species found in Indonesia comprising 89 species of tree, 5 species of palm, 19 species of liana, 44 species of soil herbs, 44 species of epiphyte and 1 species of fern. A more recent report by Noor et al. (2006) described that about 47 of 69 species of mangrove flora found in Indonesia are true mangrove species, while other 22 species are classified in associated mangrove plants.

The number of true mangrove plants species varies within the main Islands of Indonesia (Fig. 16.1), that is, 29 species in Sumatra, 36 species in Java, 30 species in the Lesser Sunda Islands, 36 species in Kalimantan, 33 species in Sulawesi, 32 species in Maluku and 34 species in Papua. The percentage of true species dominant across islands (Fig. 16.3) ranged from 61.7% to 76.6%, which was higher in Java and Kalimantan Islands, and it was lower in Sumatra. Variations in species number and/or dominant percentage throughout Indonesia regions might be mainly due to differences in environmental factors such as soil structure and texture, prolonged inundation, salinity, tidal range and freshwater inputs. However, Rivera-Monroy et al. (2017) argued that each mangrove plant species is affected by a combination of characteristics such as individual physiologies, ecology, dispersal ability, propagule buoyancy and longevity, geological circumstances, evolutionary rates and the genesis of each taxon.

Taxonomically, the 47 species of true mangrove plants distributed in the Indonesia region are belonging to 18 families and 21 genera (Table 16.2). The Rhizophoraceae family comprises 12 species followed by Avicenniaceae and Meliaceae with 5 and 4 species, respectively. Sonneratiaceae and Loranthaceae

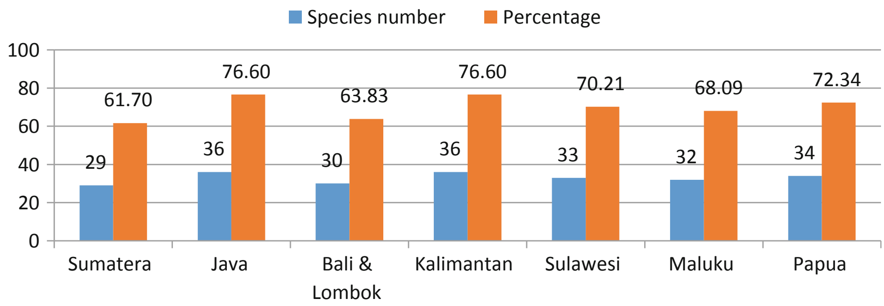

Fig. 16.3 The number of species and percentage of true mangroves growing in the main Islands of Indonesia

families comprise three species each, and the families of Acanthaceae, Myrsinaceae, Pteridaceae, Bombacaceae, Asclepiadaceae, Sterculiaceae and Combretaceae comprise two species each. The other six families including Euphorbiaceae, Lythraceae, Arecaceae, Myrtaceae and Rubiaceae comprise single species only.

Numerous mangrove species belonging to Rhizophoraceae, Avicenniaceae, Sonneratiaceae and Meliaceae families have wide distribution throughout the coastal regions of the big Islands of Indonesia, but some species are distributed in the boundary area only. For example, *Bruguiera exaristata* is found in the coastal area of West Papua only, while *Kandelia candel* is found in Sumatra and Java Islands only. Another mangrove species with limited distribution is *Aegialitis annulata* which is found only in the coastal area of Maluku, *Amyema anisomeres* belonging to Loranthaceae is distributed only in the coastal area of Sulawesi, while the *Heritiera globosa* is found in the coastal area of Kalimantan only, and *Xylocarpus mekongensis* is found in West Papua only (Table 16.2).

The dominant species of mangroves varied within the family and location. For example, Analuddin et al. (2013) reported *Rhizophora apiculata* and *R. mucronata* mangroves as the two dominant mangrove plant species in the Rawa Aopa Watumohai National Park, Southeast Sulawesi, while Prawiroatmodjo and Kartawinata (2014) found *R. apiculata* as the most dominant true mangroves in Kaimana, West Papua. The mangroves of *Avicennia marina*, *Aegiceras corniculatum* and *R. apiculata* are found as the dominant mangroves in Segara Anakan, Cilacap, Central Java (Widyastuti et al. 2018). Asadi and Pambudi (2020) reported the *Rhizophora stylosa* and *Ceriops tagal* as the two most dominant mangroves in Baluran National Park, East Java. Moreover, Irawan et al. (2021) found *R. mucronata* as the most dominant mangrove plant species in Belitung, Sumatra. Differences of dominant mangroves among Indonesia coastal areas might be due to differences in environmental setting of geomorphological condition, freshwater input, salinity, inundation regime, etc.

Other plants found in the mangrove environment in the Indonesia region are called associated mangroves. Unlike the true mangroves with high species number, the associated mangrove species in Indonesia is only found in small numbers

Table 16.2 The distribution of the true mangrove plants species in the main Islands of Indonesia

No	Family	Species	Sumatra	Java	Lesser Sunda Islands	Kalimantan	Sulawesi	Maluku	Papua
1	Acanthaceae	*Acanthus ebracteatus*	+	+	+	+	+	+	+
2		*Acanthus ilicifolius*	+	+	+	+	+	+	+
3	Pteridaceae	*Acrostichum aureum*	+	+	+	+	+	+	+
4		*Acrostichum speciosum*	+	+	+	+	+	+	+
5	Plumbaginaceae	*Aegialitis annulata*	–	–	–	–	–	+	–
6	Myrsinaceae	*Aegiceras corniculatum*	+	+	+	+	+	+	+
7	Loranthaceae	*Aegiceras floridum*	–	+	+	+	+	+	–
8		*Amyema anisomeres**	–	–	–	–	+	–	–
9		*Amyema gravis*	–	+	–	+	–	–	
10		*Amyema mackayense*	–	–	–	–	–	–	+
11	Acanthaceae	*Avicennia alba*	+	+	+	+	+	+	+
12		*Avicennia eucalyptifolia*	–	–	–	–	–	–	+
13		*Avicennia lanata*	–	–	+	+	–	–	–
14		*Avicennia marina*	+	+	+	+	+	+	+
15		*Avicennia officinalis*	+	+	+	+	+	+	+
16	Bombaceae	*Camptostemon philippinense*	–	–	–	+	+	–	–
17		*Camptostemon schultzii*	–	–	–	+	–	+	
18	Euphorbiaceae	*Excoecaria agallocha*	+	+	+	+	+	+	+
19	Asclepiadaceae	*Gymnanthera paludosa*	–	+	–	–	–	–	–
20		*Sarcolobus globosa*	–	+	–	–	–	–	–
21	Sterculiaceae	*Heritiera globosa*	–		–	+	–	–	–
22		*Heritiera littoralis*	+	+	+	+	+	+	+
23	Combretaceae	*Lumnitzera littorea*	+	+	+	+	+	+	+
24		*Lumnitzera racemosa*	–	+	+	+	+	–	–
25	Arecaceae	*Nypa fruticans*	+	+	–	+	+	–	+

(continued)

Table 16.2 (continued)

No	Family	Species	Sumatra	Java	Lesser Sunda Islands	Kalimantan	Sulawesi	Maluku	Papua
26	Myrtaceae	*Osbornia octodonta*	–	+	+	–	+	+	+
27	Lythraceae	*Pemphis acidula*	–	+	+	–	–	–	+
28	Rhizophoraceae	*Bruguiera cylindrica*	+	+	+	+	+	+	+
29		*Bruguiera exaristata*	–	–	–	–	–	–	+
30		*Bruguiera gymnorrhiza*	+	+	+	+	+	+	+
31		*Bruguiera hainesii*	+	+	+	+	+	+	+
32		*Bruguiera parviflora*	+	+	+	+	+	+	+
33		*Bruguiera sexangula*	+	+	+	+	+	+	+
34		*Ceriops decandra*	+	+	–	+	+	+	+
35		*Ceriops tagal*	+	+	+	+	+	+	+
36		*Kandelia candel*	+	–	–	–	–	–	–
37		*Rhizophora apiculata*	+	+	+	+	+	+	+
38		*Rhizophora mucronata*	+	+	+	+	+	+	+
39		*Rhizophora stylosa*	+	+	+	+	+	+	+
40	Rubiaceae	*Scyphiphora hydrophyllacea*	+	+	+	+	+	+	+
41	Sonneratiaceae	*Sonneratia alba*	+	+	–	+	+	+	+
42		*Sonneratia caseolaris*	+	+	+	+	+	+	+
43		*Sonneratia ovata*	+	+	–	+	+	+	–
44	Meliaceae	*Xylocarpus granatum*	+	+	+	+	+	+	+
45		*Xylocarpus mekongensis*	–	–	–	–	–	–	+
46		*Xylocarpus moluccensis*	+	+	+	+	+	+	+
47		*Xylocarpus rumphii*	–	+	+	–	–	+	+

Note: + Presence, – Absence

Table 16.3 Distribution of associated mangrove species on the main Islands of Indonesia

No.	Family	Species	Sumatera	Java	LSI[a]	Kalimantan	Sulawesi	Maluku	Papua
1	Lecythidaceae	*Barringtonia asiatica*	+	+	+	+	+	+	+
2	Guttiferae	*Calophyllum inophyllum*	+	+	+	+	+	+	+
3	Asclepiadaceae	*Calotropis gigantea*	+	+	+	+	+	+	+
4	Apocynaceae	*Cerbera manghas*	+	+	+	+	+	+	+
5	Verbenaceae	*Clerodendrum inerme*	+	+	+	+	+	+	+
6	Fabaceae	*Derris trifoliata*	+	+	+	+	+	+	+
7	Asclepiadaceae	*Finlaysonia maritima*	+	+	+	+	+	+	+
8	Malvaceae	*Hibiscus tiliaceus*	+	+	+	+	+	+	+
9	Convolvulaceae	*Ipomoea pes-caprae*	+	+	+	+	+	+	+
10	Melastomataceae	*Melastoma candidum*	+	+	+	+	+	+	+
11	Rubiaceae	*Morinda citrifolia*	+	+	+	+	+	+	+
12	Pandanaceae	*Pandanus odoratissimus*	+	+	+	+	+	+	+
13		*Pandanus tectorius*	+	+	+	+	+	+	+
14	Fabaceae	*Passiflora foetida*	+	+	+	+	+	+	+
15		*Pongamia pinnata*	+	+	+	+	+	+	+
16	Euphorbiaceae	*Ricinus communis*	+	+	+	+	+	+	+
27	Goodeniaceae	*Scaevola taccada*	+	+	+	+	+	+	+
18	Molluginaceae	*Sesuvium portulacastrum*	+	+	–	+	+	–	–
19	Verbenaceae	*Stachytarpheta jamaicensis*	+	+	+	+	+	+	+
20	Combretaceae	*Terminalia catappa*	+	+	+	+	+	+	+
21	Malvaceae	*Thespesia populnea*	+	+	+	+	+	+	+
22	Asteraceae	*Wedelia biflora*	+	+	+	+	+	+	+

Note: + Presence, – Absence
[a]*LSI* Lesser Sunda Islands

(Table 16.3). About 22 species of associated mangrove plants belonging to 20 families are found in Indonesia's coastal region. The families of Pandanaceae and Leguminosae comprise 2 associated mangrove species, while the other 18 families comprise single species only. Noor et al. (2006) reported that generally, the associated mangrove species are detected in the inland zone, which is not commonly inundated by seawater during high tide.

16.4.2 Fauna of Mangroves

The mangrove habitat in Indonesia supports numerous marine as well as terrestrial fauna. There are approximately 122 species of invertebrates, 45 species of fishes and 148 species of terrestrial fauna found in Indonesian mangroves. The gastropod is one of the most diverse fauna (Table 16.4), which consists of 16 families. The abundance of gastropods varied between the mangrove regions of Indonesia. For example, Baderan et al. (2019) found that *Cerithidea* spp. and *Nerita* spp. are the dominant gastropods in the mangrove ecosystem of North Sulawesi, while the *Faunus* spp. is the most dominant gastropod in mangroves of Purworejo, Central Java (Wiryanto et al. 2017).

The number of gastropod species found in Indonesian mangroves is much higher than other coastal areas of Southeast Asian countries. For example, approximately 50 species were detected in the Malay Peninsula (Ashton et al. 2003), 56 species were found in the Indian Sundarbans including areas neighbouring to mangrove trees (Dey 2006), 30 gastropod species existed in natural and restored mangroves on the west coast of Thailand (Macintosh et al. 2002), 32 species were described on the coast of South Thailand (Sri-aroon et al. 2005), and 52 species were reported in planted mangroves of Vietnam (Zvonareva et al. 2015).

Bivalve species living in Indonesian mangroves are found mostly in soft muddy habitats. There are 15 species belonging to 8 families (Table 16.5). The Ostreidae was the richest family of bivalves comprising four species including *Crassostrea cucullata*, *Crassostrea iredalei*, *Lopha folium* and *Saccostrea echinata.* Most families of bivalves are comprised of single species only. In general, the *Anadara* spp. is the most dominant bivalve species living in the mangroves of Indonesia.

A large species number of crustaceans are found in the mangroves of Indonesia. There are 8 families and 33 species (Table 16.6). The Grapsidae is the richest species of the family of crustaceans with 20 species followed by Ocypodidae with 3 species. Other families including Alpheidae and Balanidae are comprised of two species, while the families of Portunidae, Gecarcinidae, Thalassinidae and Paguridae are comprised of single species only.

There are variations in distribution of mollusc diversity in Indonesia (Table 16.7). Candri et al. (2018) found 5 bivalves and 42 gastropods living in the mangroves of Lombok Island, West Nusa Tenggara. Kaseng and Hiola (2017) found 15 bivalves and 30 gastropods living in the mangroves of Baru Regency, South Sulawesi. Islami and Mudjiono (2009) found 9 bivalves and 24 gastropod species living in mangroves

Table 16.4 Mangrove gastropod fauna in Indonesia

No	Family	Species	No	Family	Species
1	Potamididae	*Terebralia palustris* (Linnaeus)	39	Neritidae	*N. bicanaliculata*
2		*T. sulcata* (Born)	40		*N. zigzag* (Lamarck)
3		*Telescopium* (Linnaeus)	41		*N. variegata* (Lesson)
4		*T. mauritius* (Butot)	42		*N. auriculata* (Lamarck)
5		*Cerithidea djadjarensis* (Martin)	43		*Clithon corona* (Linnaeus)
6		*C. alata* (Philippi)	44		*C. ovalensis*
7		*C. obtusa* (Lamarck)	45	Thiaridae	*Melanoides riquetii* (Grateloup)
8		*C. quadrata* (Sowerby)	46		*M. tuberculata* (Muller)
9		*C. weyersi* (*Dautzenberg*)	47	Amphibolidae	*Salinator burmana* (Blanford)
10		*C. cingulata* (Gmelin)	48		*S. fragilis* (Lamarck)
11	Ellobiidae	*Cassidula aurisfelis* (Bruguire)	49	Ocypodidae	*U. signatus* (Hess)
12		*C. lutescens* (Butot)	50		*U. consobrinus* (De Man)
13		*C. mustelina* (Deshayes)	51		*U. anulipes* (H. Milne-Edwards)
14		*C. triparietalis* (Martens)	52		*U. dussumieri* (H. Milne-Edwards)
15		*C. sulculosa* (Musson)	53		*U. triangularis* (A. Milne-Edwards)
16		*Auriculastra subula* (Quoy et Gaimard)	54		*U. marionis*
17		*A. elongata*	55		*U. coartasus*
18		*Ellobium aurisjudae* (Linnaeus)	56		*U. rosea*
19		*E. aurismidae* (Linnaeus)	57		*Macrophthalmus convexus* (Stimpson)
20		*E. polita*	58		*M. telescopius* (Owen)
21		*E. tornatelliforme* (Petit)	59		*M. tridentatum*
22		*Pythia plicata* (Ferussac)	60		*M. definitus* (Adam et White)
23		*P. trigona* (Troschel)	61		*Ocypode ceratophthalma* (Phallus)
24		*P. pantherina*	62	Cerithiidae	*Cerithium morum* (Lamarck)
25		*Melampus singaporensis* (Pfeiffer)	63		*C. patulum*
26		*M. pulchellus* (Petit)	64		*Clypeomorus granosum*
27		*M. semisulcatus* (Mousson)	65	Melongenidae	*Melongena galeodes* (Lamarck)

(continued)

Table 16.4 (continued)

No	Family	Species	No	Family	Species
28	Littorinidae	*Littorina scabra* (Linnaeus)	66	Trochidae	*Monodonta labio* (Linnaeus)
29		*L. carinifera* (Menke)	67	Assimineidae	*Syncera breviculata* (Pfeiffer)
30		*L. intermedia* (Philippi)	68		*S. javana* (Thielf)
31		*L. melanostoma* (Gray)	69		*S. nitida* (Pease)
32		*L. undulata* (Gray)	70		*S. woodmasoniana* (Nevill)
33	Neritidae	*Nerita planospira* (Anto)	71	Stenothyridae	*Stenothyra glabrata* (A. Adams)
34		*N. albucilla* (*Linnaeus*)	72	Muricidae	*Chicoreus adustus*
35		*N. chameleon*	73		*Drupa margariticola*
36		*Neritina violaceae* (Gmelin)	74	Nassariidae	*Nassa olivacea*
37		*N. turrita* (Gmelin)	75		*Alectrion taenia*
38		*Faunus ater* (de Montfort)			

Table 16.5 Bivalve species found in the mangroves of Indonesia

No	Bivalvia	Species
1	Cymatiidae	*Cymatium pileare* Linne, 1758
2	Turbinidae	*Turbo bruneus* Roding, 1791
3	Ostreidae	*Crassostrea cucullata* Born, 1778
4		*Crassostrea iredalei* Quoy and Gaimard, 1836
5		*Lopha folium* Linne, 1758
6		*Saccostreae chinata* Quoy and Gaimard, 1832
7	Arcidae	*Anadara granosa* Linne, 1758
8		*Barbatia decustata* Reeve, 1844
9		*Scapharca pilula* Reeve, 1843
10	Mactridae	*Harvella plicataria* Linne, 1767
11		*Mactra violacea* Gmelin, 1791
12	Tellinidae	*Leporimeti ephippium* Spengler, 1798
13	Isognomidae	*Isognomon perna* Linne, 1758
14	Spondylidae	*Spondylus squamosus* Schreibers, 1793
15	Corbiculidae	*Polymesoda bengalensis* Lamarck, 1818

of Ambon Bay, Maluku, whereas Baderan et al. (2019) reported 3 bivalves and 21 gastropod species living in South Bolaang, North Sulawesi. Fewer species numbers of gastropods were found in the Brebes coast of Central Java (Nurfitriani et al. 2019) as well as in Mojo Village, Pemalang District, Central Jawa (Puryono and Suryanti 2019). This variation in mollusc diversity in different mangrove places of Indonesia might be due to differences in environmental factors among mangrove habitats.

Table 16.6 Crustacean species found in the mangroves of Indonesia

No	Crustacea	Species
1	Grapsidae	*Sarmatium incidum*
2		*S. crassum*
3		*M. crassipes*
4		*Sesarma taeniolata* (White)
5		*S. meinerti* (De Man)
6		*S. edwardsii*
7		*S. bataviana* (De Man)
8		*S. moeschi*
9		*S. cumolpe* (De Man)
10		*S. smithi* (H. Milne-Edwards)
11		*S. bocourti* (A. Milne-Edwards)
12		*S. fasciata* (Lanchester)
13		*S. palawanensis*
14		*S. videns* (De Hans)
15		*S. onychophora* (De Man)
16		*S. rousseauxi* (H. Milne-Edwards)
17		*S. erythrodeactylum* (Hess)
18		*S. longipes* (Krauss)
19		*Metopograpsus latifrons* (White)
20		*Uca vocans* (Linnaeus)
21		*U. lactea* (De Haan)
22	Ocypodidae	*O. arenaria* (De Man)
23		*O. cardimana*
24		*Ilyoplax delsmani* (De Man)
25		*Tylodiplax indian*
26	Portunidae	*Scylla serrata* (Forskal)
27	Gecarcinidae	*Cardisoma carnifex* (Herbst)
28	Thalassinidae	*Thalassina anomala* (Herbst)
29	Alpheidae	*Alpheus crassimanus* (Heller)
30		*A. bisincisus* (De Man)
31	Paguridae	*Coenobita cavipes* (Stimpson)
32	Balanidae	*Balanus* spp.
33		*Clibanarius* spp.

Numerous fishes are frequently found in the mangroves of Indonesia. It was reported that about 45 species of fish are found associated with the mangrove environment of Indonesia (LPP Mangrove 2000). Wahyudewantoro (2018) reported 38 species of fish belonging to 20 families found in the mangroves of Lombok.

The fishes found in mangroves are predominated by *Mugil* sp., *Sillago* sp., *Johnius* sp., *Trachiphalus* sp., *Cynoglossus* sp., *Setipine* sp. and *Leiognathus* sp. The common fish species of commercial interest in Indonesia are mullets (*Mugil* sp.), milkfish (*Chanos chanos*), tilapia (*Cichlidae* spp.), snappers (*Lutjanidae*

Table 16.7 The diversity of molluscs in mangrove ecosystems at several coastal regions of Indonesia

Location	No. of bivalve	No. of gastropod	References
Ambon Bay, Maluku	9	24	Islami and Mudjiono (2009)
Aceh Besar and Banda Aceh, Aceh	5	14	Irma and Sofyatuddin (2012)
Nirvana Coast, Padang City, West Sumatra	–	15	Yolanda et al. (2015)
Baru Regency coast, South Sulawesi	15	30	Kaseng and Hiola (2017)
Lombok Island, West Nusa Tenggara	5	42	Candri et al. (2018)
South Bolaang Mongondow, North Sulawesi	3	21	Baderan et al. (2019)
Brebes, Central Java	–	10	Nurfitriani et al. (2019)
Mojo Village, Pemalang District, Central Java	–	8	Puryono and Suryanti (2019)
Pamekasan coast, East Jawa	–	16	Islamy and Hasan (2020)
Kolaka, Southeast Sulawesi	4	19	Hasidu et al. (2021)

spp.) and sea bass (*Lates calcarifer*). The most common fish is perhaps the mudskippers (*Periophthalmus* spp.), which is endemic to the mangroves.

Terrestrial organisms are found frequently associated with mangroves of Indonesia. A high diversity of terrestrial vertebrates was found in the mangroves of Indonesia including 76 species of birds, 34 species of squamata, 12 species of carnivores, 11 species of testudinate, 6 species of amphibian and 4 species of crocodiles (LPP Mangrove 2000) as shown in Fig. 16.4. More than 50% of vertebrates found in mangroves are birds, and 20% are belonging to squamata and 8.1% to testudinate. There are few amphibians (4.1%), Artiodactyla (3.4%) and crocodile (2.7%). However, some threatened mammal species, such as *Bubalus* sp., were found using mangroves as an important home range and looking for food (Septiana et al. 2016). Additionally, other various species of insects are also found inhabiting the mangroves of Indonesia including *Cyptophora beccani*, *Aeshnidae* sp., *Lycaenidae* sp., *Drosophila* sp., *Apterone mobius*, *Culicidae* sp., etc.

16.5 Phytoplankton and Zooplankton Diversity

Plankton, ‘the unseen aquatic organism’, are the microscopic plants and animals that drift about in the water, allowing currents, tides and other factors to determine their mobility. Plankton provides food to a wide variety of species as the foundation of freshwater and seawater food pyramids. Plankton communities assume very great ecological significance in mangrove ecosystems, as this ecosystem serves feeding,

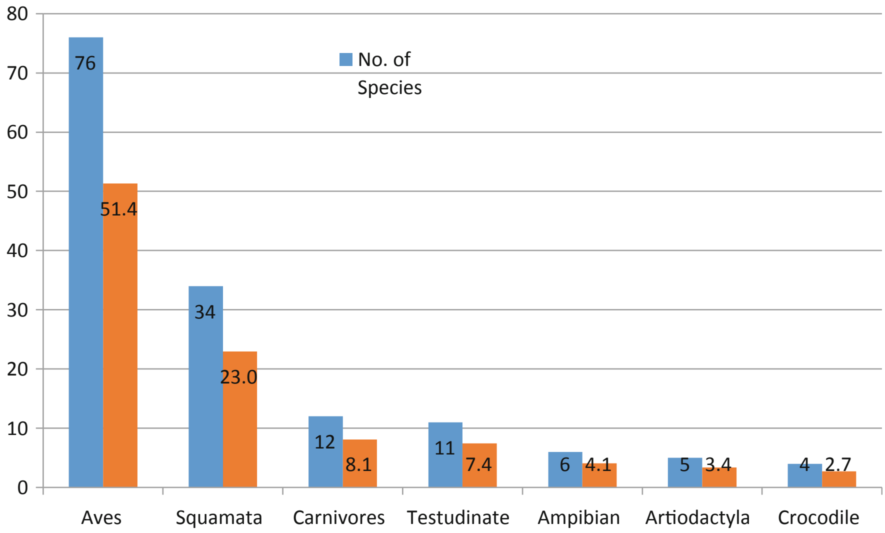

Fig. 16.4 The number and percentage of terrestrial fauna living in the mangroves of Indonesia

breeding and nursery grounds (Silambarasan et al. 2016). There are two main types of plankton: phytoplankton, which comprises plants, and zooplankton, which comprises animals. In the coastal and estuarine ecosystems, free floating microalgae photoautotrophic communities referred to as phytoplankton account for approximately half the production of organic matter on Earth (Mitra 2013). Zooplankton is a primary consumer that plays a substantial role in the aquatic environment that transfers energy from primary producers (phytoplankton and bacteria) to higher trophic levels (Pratiwi et al. 2016).

Although studies have been made on marine and estuarine plankton in many countries, knowledge of plankton in mangrove areas specifically is very scanty in the world (Mitra 2013). Saifullah et al. (2016) gathered the information for some tropical countries with mangroves and reported research findings on phytoplankton in mangrove areas (Fig. 16.5).

Research activity and findings on plankton specifically in mangrove habitats have been previously reported in Sumatra, Java and Sulawesi (Fig. 16.6).

The species composition and abundance of plankton (phytoplankton and zooplankton) in Indonesian mangrove regions vary considerably between regions and seasons (Table 16.8). The difference in plankton existence among sites could be also affected by many factors. The phytoplankton distribution and productivity of an estuary depend on various physico-chemical factors such as salinity, pH, temperature, dissolved oxygen, turbidity (Silambarasan et al. 2016; Saifullah et al. 2016), anthropogenic activities (Mulyadi et al. 2019) and nutrients (Aryawati et al. 2021). In Indonesian mangrove areas, the reported greatest number of phytoplankton taxa was found in Aceh Tamiang (Sumatra), Segara Anakan-Cilacap (Java) and

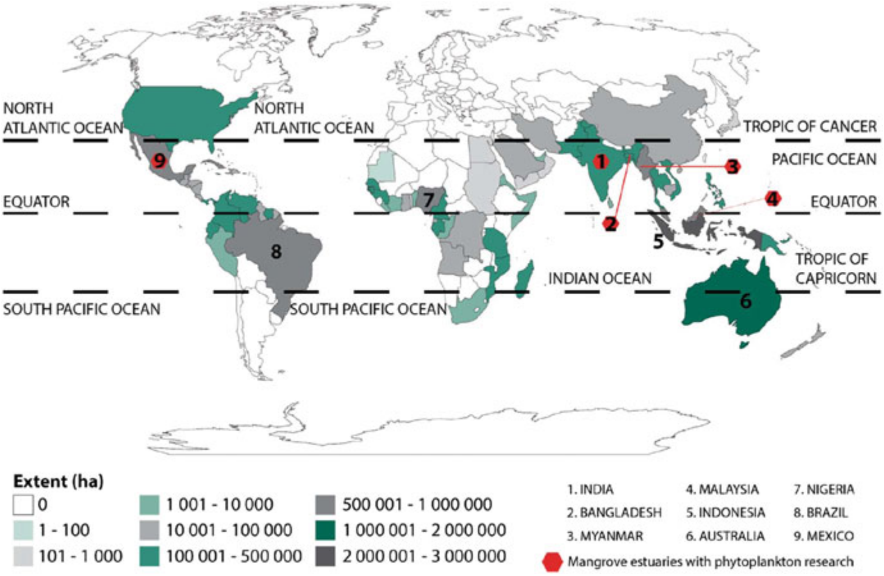

Fig. 16.5 Some major tropical countries with mangrove and reported research on phytoplankton in mangrove areas (Saifullah et al. 2016)

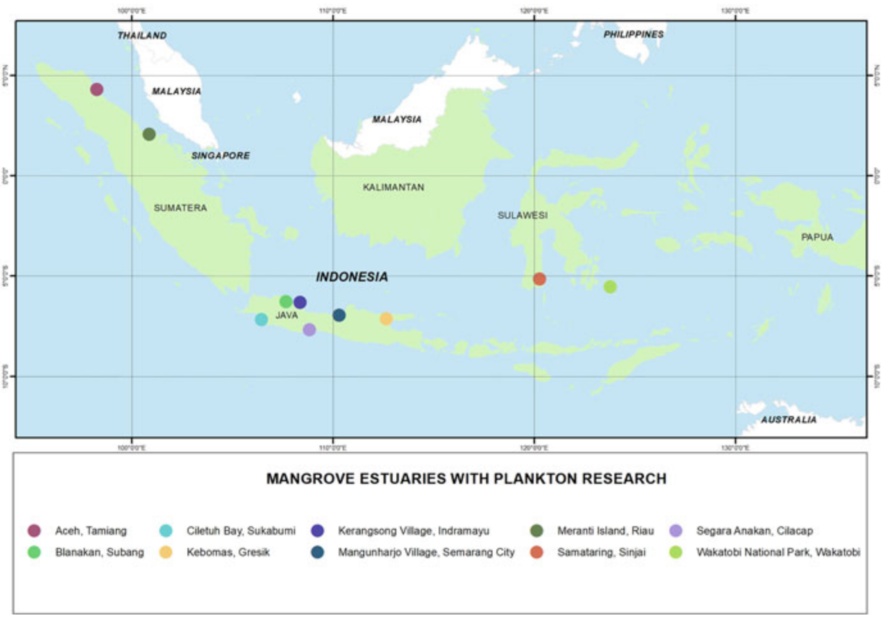

Fig. 16.6 Mangrove areas with plankton research in Indonesia

Table 16.8 Plankton composition and abundance in the mangrove area of Indonesia

Mangrove sites	Sampling time	Plankton type	Number of taxa	Abundance	References
Lubuk Damar, Aceh Tamiang	August 2017 (dry season)	Phytoplankton	42	64,000–920,000 cell/m^3	Darmarini et al. (2021)
	January 2018 (rainy season)	Phytoplankton	56	23,484,311–190,315,789 cell/m^3	
Meranti Island, Riau	–	Phytoplankton	23	10,675–24,290 ind/L	Hilmi et al. (2020)
		Zooplankton	8	261–2204 ind/L	
Mangunharjo, Semarang City	May–September 2016	Phytoplankton	25	–	Hastuti et al. (2018)
		Zooplankton	8	–	
Blanakan, Subang	September 2010	Phytoplankton	5	9152 ind/L	Heriyanto (2012)
		Zooplankton	1	2112 ind/L	
Karangsong, Indramayu	July 2016	Phytoplankton	9	3750–8750 ind/L	Sihombing et al. (2017)
		Zooplankton	2	1250 ind/L	
Segara Anakan, Cilacap	April–May 2019 (transition season I)	Phytoplankton	50	1133 ind/L	Piranti et al. (2021), Asiddiqi et al. (2019)
	August–September 2019 (dry season)	Phytoplankton	58	1695 ind/L	
Ciletuh Bay, Sukabumi	–	Zooplankton	42	8–72 ind/L	Riyantini et al. (2020)
Kebomas, Gresik	January 2019	Zooplankton	–	380–2305 ind/L	Pangestika and Insafitri (2020)
Samataring, Sinjai	January 2003	Phytoplankton	23	792–1476 ind/L	Qiptiyah et al. (2008)
		Zooplankton	6	36–72 ind/L	
Wakatobi National Park, Wakatobi	July 2004	Phytoplankton (diatom)	95	–	Horton et al. (2006)

Wakatobi (Sulawesi). The phytoplankton species found in the mangrove waters of Aceh Tamiang and Segara Anakan at different seasons are listed in Table 16.9.

There were 95 phytoplankton taxa in the mangrove area of Aceh Tamiang and Segara Anakan-Cilacap composed of 7 classes. Bacillariophyceae, also known as diatoms, was the most dominant species in the mangrove area (73.7%) followed by Dinophyceae (8.4%). The high abundance of Bacillariophyceae was a common occurrence at sea and estuary and had higher reproducibility compared to other phytoplankton (Aryawati et al. 2017). It was also supported by the fact that this

Table 16.9 The phytoplankton taxa found in the mangrove area of Aceh Tamiang (Sumatra) and Segara Anakan-Cilacap (Java) at different seasons (Darmarini et al. 2021; Piranti et al. 2021; Asiddiqi et al. 2019)

	Mangrove area	Aceh Tamiang (Sumatra)		Segara Anakan-Cilacap (Java)
No	Season	Dry	Rainy	Transition I
A.	Class of Bacillariophyceae			
1	*Actinoptychus* sp.	–	+	–
2	*Amphiprora* sp.	+	+	–
3	*Amphora* sp.	+	+	–
4	*Arachnoidiscus* sp.	–	+	–
5	*Asterionella* sp.	–	–	+
6	*A. japonica*	–	–	+
7	*A. formosa*	–	–	+
8	*Auliscus* sp.	–	+	–
9	*Bacillaria* sp.	–	+	–
10	*Bacteriastrum* sp.	+	+	–
11	*Bellerochea* sp.	–	+	–
12	*Biddulphia* sp.	+	+	–
13	*Campylodiscus* sp.	+	+	–
14	*Chaetoceros* sp.	+	+	–
15	*C. affinis*	–	–	+
16	*C. diversus*	–	–	+
17	*C. didymus*	–	–	+
18	*C. lauderia*	–	–	+
19	*C. senescence*	–	–	+
20	*C. socialis*	–	–	+
21	*C. weissflogii*	–	–	+
22	*Climacodium* sp.	–	+	–
23	*Cocconeis* sp.	+	+	–
24	*Corethron* sp.	+	+	–
25	*Coscinodiscus* sp.	+	+	–
26	*C. marginatus*	–	–	+
27	*C. lineatus*	–	–	+
28	*Diatoma vulgare*	–	–	+
29	*Diploneis* sp.	+	+	–
30	*Ditylum* sp.	+	+	–
31	*Eucampia* sp.	–	+	–
32	*Fragilaria* sp.	–	+	–
33	*Gomphonema* sp.	–	+	–
34	*Gossleriella* sp.	–	+	–
35	*Grammatophora angulosa*	–	–	+
36	*Guinardia* sp.	+	+	–
37	*Gyrosigma* sp.	–	+	–
38	*G. balticum*	–	–	+
39	*G. strigilis*	–	–	+

(continued)

Table 16.9 (continued)

	Mangrove area	Aceh Tamiang (Sumatra)		Segara Anakan-Cilacap (Java)
No	Season	Dry	Rainy	Transition I
40	*Hemiaulus* sp.	+	+	–
41	*Lauderia* sp.	+	+	–
42	*Leptocylindrus* sp.	+	+	–
43	*Melosira* sp.	–	+	–
44	*M. italica*	–	–	+
45	*Mastogloia* sp.	+	+	–
46	*Navicula* sp.	–	+	+
47	*N. placentula*	–	–	+
48	*Nitzschia* sp.	+	+	–
49	*N. longissima*	–	–	+
50	*N. sigma*	–	–	+
51	*N. gracilis*	–	–	+
52	*Planktoniella* sp.	–	+	–
53	*Pleurosigma* sp.	+	+	–
54	*P. intermedium*	–	–	+
55	*Rhabdonema* sp.	–	+	–
56	*Rhizosolenia* sp.	+	+	–
57	*R. alata*	–	–	+
58	*R. longiseta*	–	–	+
59	*Skeletonema* sp.	–	+	–
60	*Stephanopyxis* sp.	–	+	–
61	*Streptotecha* sp.	+	+	–
62	*Surirella* sp.	–	+	–
63	*Synedra acus*	–	–	+
64	*S. tabulata*	–	–	+
65	*Tabellaria* sp.	–	–	+
66	*Thalassionema* sp.	–	+	–
67	*Thalassiosira* sp.	+	+	–
68	*Thalassiothrix* sp.	–	+	–
69	*T. nitzschioides*	–	–	+
70	*Triceratium* sp.	+	+	–
B.	Class of Dinophyceae			
71	*Ceratium* sp.	–	+	–
72	*C. belone*	–	–	+
73	*Dinophysis* sp.	+	+	–
74	*Gonyaulax* sp.	–	+	–
75	*Ornithocercus* sp.	–	+	–
76	*Peridinium* sp.	+	+	–
77	*Prorocentrum* sp.	–	+	–
78	*Protoperidinium* sp.	+	+	–
C.	Class of Chlorophyceae			

(continued)

Table 16.9 (continued)

	Mangrove area	Aceh Tamiang (Sumatra)		Segara Anakan-Cilacap (Java)
No	Season	Dry	Rainy	Transition I
79	*Chlorella variegata*	–	–	+
80	*Chlorococcum humicola*	–	–	+
81	*Chodatella quadriseta*	–	–	+
82	*Eudorina elegans*	–	–	+
83	*Halosphaera* sp.	+	–	–
84	*Volvox aureus*	–	–	+
D.	Class of Cyanophyceae			
85	*Chroococcus giganteus*	–	–	+
86	*Oscillatoria* sp.	+	–	–
87	*O. limosa*	–	–	+
88	*O. formosa*	–	–	+
89	*Spirulina* sp.	–	–	+
90	*Trichodesmium* sp.	–	+	–
E.	Class of Charophyceae			
91	*Hyalotheca mucosa*	–	–	+
92	*Spyrogyra azygospora*	–	–	+
93	*Zygnemopsis americana*	–	–	+
F.	Class of Euglenophyceae			
94	*Phacus pleuronectes*	–	–	+
G.	Class of Chrysophyceae			
95	*Dictyocha* sp.	–	+	–
	Total species	27	51	43

Note: + Presence, – Absence

phytoplankton class was cosmopolitan, had high reproductive power and was resistant to extreme conditions (Piranti et al. 2021; Aryawati et al. 2021).

Based on spatial distribution, almost all phytoplankton taxa found in the mangrove area of Aceh Tamiang (Sumatra) were absent in the Segara Anakan mangrove (Java). Only *Navicula* sp. was found in both mangrove areas. *Navicula* is a genus of boat-shaped diatom algae that is common in both freshwater and marine habitats, cosmopolitan and present throughout the year (Guiry and Guiry 2013).

Temporal distribution showed that the rainy season had more phytoplankton (51 species) in the mangrove area than the dry season (27 species) and transition season (43 species). The high composition of phytoplankton during the rainy season might be related to nutrient escalation in the water's surface for consumption by phytoplankton (Darmarini et al. 2021). The nutrients were influenced by water hydrodynamics and seasonal cycling acting as a driving factor for phytoplankton abundance and productivity. Aryawati et al. (2016) have established that nutrients like nitrates, phosphate and silicate positively correlated with phytoplankton distribution and abundance in tropical estuaries.

The fertility and health of mangrove environments might be indicated by the productivity of phytoplankton and zooplankton as primary and secondary producers, respectively (Saifullah et al. 2016). However, mangrove is a ‘detritus-based ecosystem’ that supplies the ecosystem ambient water with nutrients, which thus supports the development and growth of the planktonic community in the water environments (Mitra 2013) and zooplankton growth. Mangrove ecosystems were claimed to be important breeding and feeding grounds for zooplankton and fishery resources due to the role of organic matter, especially derived from decomposed mangrove litter detritus.

There is limited information about the number of zooplankton taxa in Indonesian mangrove areas compared with phytoplankton taxa. Riyantini et al. (2020) found the difference in zooplankton composition at different mangrove zonation in Sukabumi (Table 16.10).

The composition of zooplankton in *R. mucronata* zones was higher than *L. racem*osa zonation presumed related to mangrove biomass and litterfall rate. The mangroves are known to produce organic matter, to accumulate and store carbon and nutrients and then to lose biomass as litterfall. Analuddin et al. (2020) reported that *R. mucronata* had above-ground biomass higher than *L. racemosa.* Mangrove biomass litter was the most important source of food and energy for many living organisms in the coastal ecosystem, and the higher species number of zooplankton in *R. mucronata* zones correlates to higher biomass and litterfall.

Plankton has an essential role in the food chain in aquatic ecosystems and is often used as indicators of stability, fertility and water quality (Aryawati et al. 2017). Plankton diversity is frequently seen as an indicator of habitat characterization and the status of ecological systems with a relationship with productivity (Effendi et al. 2016). The plankton diversity in the mangrove area of Indonesia is listed in Table 16.11.

Plankton communities are multispecies communities, which are highly multifaceted in terms of their diversity and dynamics (Silambarasan et al. 2016). The Shannon diversity index of phytoplankton in some mangrove areas of Indonesia ranged from 0.83 to 2.83 and 0.47 to 3.00 for zooplankton. Mitra (2013) reported that Shannon-Wiener species diversity index (H) of Nayachar Island for phytoplankton and zooplankton temporally was 2.79–2.99 and 1.77–1.93, respectively. In Sundarbans, the biggest mangrove area in the world, the result of the Shannon diversity index of phytoplankton from 2000 to 2010 ranged from 3.59 to 3.9 (Mitra 2013). A low value of Shannon H' indicates domination by a few species; a high value pointed a large number of species with similar abundances. As the spawning, nursery and feeding ground for many estuary organisms, mangroves in good condition will support the escalation of plankton biodiversity.

The evenness similarity index of phytoplankton in the mangrove area was 0.11–0.87 and the Simpson dominance index 0.08–0.73. Change in species dominance of plankton in mangrove ecosystems is a frequently observed phenomenon especially in response to diurnal and seasonal change. The domination of phytoplankton species from Bacillariophyceae class in almost all mangrove areas of Indonesia suggests that the water may have been enriched with nutrients.

Table 16.10 The zooplankton genus is found in the mangrove area of Sukabumi at different zonation (Riyantini et al. 2020)

No	Genus of zooplankton	Mangrove zonation	
		L. racemosa	*R. mucronata*
1	*Amoeba*	+	+
2	*Arcicella*	+	+
3	*Brachionus*	+	+
4	*Bryocamptus*	–	+
5	*Bursaria*	+	+
6	*Canthocampus*	+	–
7	*Centropyxis*	+	+
8	*Chironomus*	–	+
9	*Cyrtolophosis*	–	+
10	*Chydorus*	+	+
11	*Cyclops*	+	+
12	*Cypria*	–	+
13	*Cypridopsis*	+	–
14	*Coleps*	+	+
15	*Colurella*	–	+
16	*Diaptomus*	–	+
17	*Euglypha*	–	+
18	*Tanytarsus*	–	+
19	*Globorotalia*	–	+
20	*Ichtydium*	+	+
21	*Keratella*	+	+
22	*Lecane*	–	+
23	*Lepadella*	+	+
24	*Lionotus*	–	+
25	*Moina*	–	+
26	*Monostyla*	+	+
27	*Nauplius*	+	+
28	*Nebela*	–	+
29	*Notholca*	+	+
30	*Paramecium*	+	+
31	*Philodina*	+	+
32	*Panagrellus*	+	+
33	*Peridinium*	–	+
34	*Platyias*	+	+
35	*Plumatella*	+	–
36	*Polyarthra*	+	+
37	*Rotaria*	–	+
38	*Stentor*	–	+
39	*Stylonychia*	+	+
40	*Squatinella*	+	+
41	*Tetrahymena*	+	+

(continued)

Table 16.10 (continued)

No	Genus of zooplankton	Mangrove zonation	
		L. racemosa	*R. mucronata*
42	*Vorticella*	–	+
	Total genus	25	39

Note: + Presence,
– Absence

Bacillariophyceae distribution and abundance are associated with the concentration of nutrients (Jakovljevic et al. 2016). Plankton are very sensitive to the change in environment and can therefore act as indicators of water quality.

16.6 Ecosystem Services and Livelihoods

Mangroves play an important role to support local and regional coastal communities with ecosystem services (ES) and thus increase the livelihoods of communities. They support a wide range of ecosystem services for provisioning, regulating and supporting and cultural services to millions of coastal communities in Indonesia (Tables 16.12, 16.13, and 16.14). ES in mangroves also benefit human well-being (Duke et al. 2014; Potschin and Haines-Young 2016).

Table 16.12 shows the studies carried out in Indonesia on provisioning services; this includes wood, timber, fuelwood and log production derived from, for example, mangrove forest concession right at Kalimantan and Sulawesi Islands (Burbridge and Koesoebiono 1982) or commercial mangrove species, *Rhizophora apiculata* and *Bruguiera gymnorrhiza* from Tanjung Bungin, Banyuasin, South Sumatra (Sukardjo 1987). On the coast of South Sulawesi, timber and fuelwood have been exploited since 1965 (Nurkin 1994). These products are harvested on both small and large scales, helping to support local livelihoods and national exports (Lahjie et al. 2019).

Fisheries and derivatives such as fish production are also important provisioning services (Table 16.12), and studies have been done at numerous sites, North Sumatra and Aceh (Basyuni et al. 2018a, b, c, Basyuni et al. 2021; Fitri et al. 2018), Centra Java (Ismail et al. 2018a, b), South Sumatra (Sukardjo 2004; Eddy et al. 2016). Local communities harvest shrimp, eel, clams, crabs, sea snails and a variety of fish species from mangrove ecosystems, providing income and food for families (Armitage 2002) (Fig. 16.7).

Ecosystem services are ecological processes or ecosystem components that can provide benefits to the community, especially the community around the mangrove ecosystem. A mangrove ecosystem is able to provide service benefits as a protector of coastal areas, both which can be felt directly or indirectly. ES can even be used to support environmental management; integrated coastal area development policies can maintain environmental quality and the sustainability of coastal ecosystems

Table 16.11 The plankton diversity in the mangrove area of Indonesia

Mangrove sites	Sampling time	Plankton organism	Plankton diversity indices			References
			Shannon diversity index (H')	Evenness similarity index (E)	Simpson dominance index (C)	
Lubuk Damar, Aceh Tamiang	August 2017	Phytoplankton	1.24–2.83	0.11–0.87	0.08–0.48	Darmarini et al. (2021)
	January 2018	Phytoplankton	0.83–2.35	0.23–0.64	0.17–0.73	
Meranti Island, Riau	–	Phytoplankton	1.75–2.14	0.66–0.75	0.15–0.24	Hilmi et al. (2020)
		Zooplankton	0.86–1.61	0.79–0.83	0.24–0.46	
Mangunharjo, Semarang City	May–September 2016	Phytoplankton	–	–	–	Hastuti et al. (2018)
		Zooplankton	–	–	–	
Blanakan, Subang	September 2010	Phyto- and zooplankton	1.242	0.128	0.368	Heriyanto (2012)
Karangsong, Indramayu	July 2016	Phyto- and zooplankton	1.332	0.152	0.28	Sihombing et al. (2017)
Segara Anakan, Cilacap	April–May 2019 (dry season)	Phytoplankton	–	–	–	Piranti et al. (2021); Asiddiqi et al. (2019)
	August–September 2019 (rainy season)	Phytoplankton	–	–	–	
Ciletuh Bay, Sukabumi	–	Zooplankton	0.47–1.42	0.21–0.41	0.44–0.74	Riyantini et al. (2020)
Kebomas, Gresik	January 2019	Zooplankton	1.73–3.00	0.99	0.07–0.16	Pangestika and Insafitri (2020)
Samataring, Sinjai	January 2003	Phyto- and zooplankton	2.402–2.633	0.831–0.852	0.102–0.134	Qiptiyah et al. (2008)
Wakatobi National Park, Wakatobi	July 2004	Phytoplankton (diatom only)	–	–	–	Horton et al. (2006)

Table 16.12 Ecosystem services for provisioning studies in Indonesia

Mangrove sites/species	Ecosystem services	References
Bintuni Bay, West Papua	Wood and timber	Sillanpää et al. (2017)
Coast of South Sulawesi	Timber, fuelwood	Nurkin (1994)
Tanjung Bungin, Banyuasin, South Sumatra	Wood	Sukardjo (1987)
Forest concession, Kalimantan and Sulawesi	Log production	Burbridge and Koesoebiono (1982)
Balikpapan Bay, East Kalimantan	Wood production	Lahjie et al. (2019)
Percut Sei Tuan, Jaring Halus, Pulau Sembilan, Pulau Kampai (North Sumatra), Langsa (Aceh)	Fish production	Basyuni et al. (2021)
Lubuk Kertang, North Sumatra	Fishery production	Fitri et al. (2018)
Segara Anakan, Central Java	Coastal fisheries	Ismail et al. (2018a, b)
Apar Bay, East Kalimantan, Banyuasin Estuary, South Sumatra	Fish diversity	Sukardjo (2004)
Air Telang Protected Forest (ATPF)	Sustainable fisheries, silvofishery	Eddy et al. (2016)
Percut Sei Tuan, North Sumatra	Silvofishery for fish, shrimp and crab	Basyuni et al. (2018a, b, c)
Lubuk Kertang Forest, North Sumatra	Silvofishery pond, silvofishery for milkfish production, silvofishery for tiger shrimp and silvofishery for mud crab	Basyuni et al. (2019a, b, 2020a, b)
Delta Mahakam, East Kalimantan	Silvofishery	Susilo et al. (2019)
Sinjai, South Sulawesi and Cikiong and Blanakan, West Java	Silvofishery (*empang parit*)	Fitzgerald Jr (2000)
Kutai National Park, East Kalimantan	Silvofishery	Sulistyorini et al. (2018)
Mangunharjo, Semarang City, Central Java	Silvofishery	Hastuti and Budihastuti (2016)
Kayeli Bay, Buru, Maluku	Silvofishery	Wamnebo et al. (2018)
Kandelia candel, *Lumnitzera racemosa*, *Avicennia marina*, *Pongamia pinnata*	Anti-SARS-CoV-2 infection	Illian et al. (2021)
Avicennia marina, *Xylocarpus granatum*	Antioxidant activity	Rahmawati et al. (2019)
Sixteen mangrove from Lubuk Kertang and Pulau Sembilan, North Sumatra	Antimicrobial, antifungal and antioxidant activity	Sumardi et al. (2018)
Seventeen mangrove species from Lubuk Kertang	Anticancer colon activity	Sari et al. (2018a)
Avicennia marina, *A. lanata*, *A. alba*, Lubuk Kertang, North Sumatra	Polyisoprenoids as anticancer colon	Illian et al. (2018, 2019), Qurrohman et al. (2020)
Nypa fruticans, Rhizophora mucronata, *Ceriops tagal*, Lubuk Kertang, Langkat, North Sumatra	Polyisoprenoids as anticancer colon	Sari et al. (2018b, c), Istiqomah et al. (2020), Istiqomah et al. (2021)

(continued)

Table 16.12 (continued)

Mangrove sites/species	Ecosystem services	References
Rhizophoraceae leaves, Bulaksetra, Pangandaran, West Java	Phytochemical compounds	Nurzaman et al. (2018)
Mendalok, Mempawah, West Kalimantan	Ethnobotany	Arbiastutie et al. (2021)
Malang, East Java	Biodiversity	Abidin et al. (2021)
Purworejo, Central Java	Biodiversity	Wiryanto et al. (2017)
Takalar, South Sulawesi	Biodiversity	Malik et al. (2015)
Rawa Aopa Watumohai National Park, Southeast Sulawesi	Fruit bioprospecting	Analuddin et al. (2019)
Pulau Sembilan, North Sumatra	Functional food	Basyuni et al. (2021)
Bruguiera gymnorrhiza, Kartika Jaya, Kendal, Central Java	Flour	Muryati and Subandriyo (2015)
Sonneratia alba	Fruit flour and starch	Jariyah et al. (2014)
S. caseolaris, Purworejo, Central Java	Fibres	Wibawanti et al. (2021)
Segara Anakan Lagoon, Central Java	Tannin	Hilmi et al. (2021)
Demak, Central Java	Tannin	Rejeki et al. (2019)
A. marina	Tannin	Jamarun et al. (2021)
A. marina	Fodder	Jamarun et al. (2021)

(Suwarno et al. 2016; Rumahorbo et al. 2020). Various coastal ecosystem services regarding with regulating and supporting studies are presented in Table 16.13.

Mangrove cultural ES in Indonesia is summarized in Table 16.14. This ES includes ecotourism in some mangrove sites from Sumatra, Java and Sulawesi. Segara Anakan Lagoon is an important example for cultural services utilization, such as mangrove dynamic and virtual-cultural heritage.

Indonesian mangroves are also well known to provide benefits to the local communities and support their livelihoods. Some studies have been shown that mangroves play a vital function to effective management resource use and livelihood support in Central Java, sustainable livelihoods in small-scale fisheries across Indonesian archipelago, improved livelihoods following the 2004 Indian tsunami and supporting the livelihood of the local community in the coastal of East Lombok (Table 16.15).

The mangrove ecosystem serves an ecological purpose (Armitage 2002). Mangroves provide habitat for a wide range of species. The mangrove ecosystem leads to the creation of productive habitats (Idrus et al. 2019; Damastuti and de Groot 2017). It may benefit coastal fisheries for prawns and fish by serving as a source of food for locals. Other new human well-being services, such as ecotourism and education, are being developed to transform the function of the mangrove ecosystem (Ambarita et al. 2018; Basyuni et al. 2018b; Malik et al. 2019). In this case, the combination of

Table 16.13 Ecosystem services for regulating and supporting studies in Indonesia

Mangrove sites	Ecosystem services	Reference
Sembilang, Kubu Raya, Tanjung Puting, Cilacap, Bintuni, Teminabuan, Timika, Bunaken	Global climate change mitigation	Murdiyarso et al. (2015)
Sumatra, Kalimantan, Sulawesi, Papua, Java, Bali Nusa Tenggara, Maluku for carbon stock	Climate change mitigation	Sidik et al. (2021)
Physical model of a wave flume, Institut Teknologi Bandung	Coastal protection	Yuanita et al. (2021)
Across Papuan mangroves	Organic carbon burial, soil stabilization and control	Sasmito et al. (2020)
Demak, Central Java	Coastal protection	Triyanti et al. (2017)
Mangunharjo, Semarang City, Central Java	Environmental quality	Hastuti and Budihastuti (2016)
The coastal region of Probolinggo, East Java	Water quality	Guntur et al. (2018)
Kayeli Bay, Buru, Maluku	Water quality	Wamnebo et al. (2018)
Lubuk Kertang, North Sumatra	Water quality	Basyuni et al. (2018c)
Percut Sei Tuan, Jaring Halus, Pulau Sembilan, Pulau Kampai (North Sumatra), Langsa (Aceh)	Nutrient content	Basyuni et al. (2021)
Karimun Java Island	Soil carbon stock	Nehren and Wicaksono (2018)
Rhizophora apiculata, *Avicennia officinalis*, *Bruguiera cylindrica*, *Xylocarpus granatum*	Anti-salt tolerance	Basyuni et al. (2017a, b), 2019c)
South Sulawesi	Soil stabilization and erosion control	Weinstock (1994)
Segara Anakan Lagoon, Central Java	Support mudflat and sand flat	Ardli and Wolff (2009)
(Ulumuddin et al. 2021)	Support for coral reefs	Ulumuddin et al. (2021)
Hurun Bay, Lampung and Awerange Bay, South Sulawesi	Support for coral reefs	Alongi et al. (2008)
Takalar, South Sulawesi	Provision of nursery habitats	Malik et al. (2015)
Apar Bay, East Kalimantan, Banyuasin Estuary, South Sumatra	Provision of nursery habitats	Sukardjo (2004)

mangrove use from goods and services is a utilization strategy to achieve the goals of mangrove conservation and diversification of local communities' livelihoods.

Table 16.14 Ecosystem services for cultural mangrove studies in Indonesia

Mangrove sites	Ecosystem services	Reference
Bebanga, Mamuju, West Sulawesi	Ecotourism	Malik et al. (2019)
Margasari, East Lampung	Ecotourism	Setiawan et al. (2017)
North coast of Indramayu, West Java	Dynamic mangrove	Gunawan et al. (2017)
Lubuk Kertang and Kampung Nipah, North Sumatra	Ecotourism	Basyuni et al. (2018b) Ambarita et al. (2018)
Labuan Uki Bay, Bolaang Mongondow, North Sulawesi	Ecotourism	Lasabuda et al. (2019)
Segara Anakan Lagoon, Central Java	Dynamic mangrove	Nordhaus et al. (2019)
Segara Anakan, Ujung Kulon National Park, Seribu Island Marine park	Virtual-cultural heritage	Sukardjo (1991)

Fig. 16.7 Silvofishery in Lubuk Kertang, designed by a collaboration between the university and local communities

Table 16.15 Benefits of mangrove to local communities and support livelihood studies in Indonesia

Mangrove sites	Ecosystem services	References
Coastal of East Lombok	The livelihood of local communities	Idrus et al. (2019)
Four villages: Sriwulan, Bedono, Timbulsloko and Surodadi	Sustainable resource use and livelihood support	Damastuti and de Groot (2017)
Indonesian archipelago	Sustainable livelihoods in small-scale fisheries	Stacey et al. (2019)
Banda Aceh	Livelihood changes after the 2004 Indian Ocean tsunami	Ismail et al. (2018a, b)

16.7 Global Change and Anthropogenic Threats and Conservation

Mangroves in Indonesia have faced direct human-made threats including deforestation and forest conversion to other land uses. These threats contribute to significant mangrove loss, along with their other important ecosystem functions provided by mangroves to coastal habitats as well as community livelihoods. In addition, there are also indirect anthropogenic drivers such as sea level rise and climate change as well as non-anthropogenic threats that commonly occur naturally, such as extreme weather and climate, tsunami and other geological events. Although the mangrove ecosystem has been known for its great resilient capacity towards these disturbances, the area of mangrove in Indonesia has been steadily decreasing over time. In Southeast Asia between 2000 and 2012, the mangrove ecosystem was lost at rates of 0.18% per year on average (Richards and Friess 2016). It was mainly caused by aquaculture expansion replacing mangrove ecosystems and their ecological functions.

There were approximately 4.3 Mha of mangrove area in Indonesia in 1980 (Murdiyarso et al. 2015). However, the mangrove area continuously declined up to 26% in the following 20 years (Murdiyarso et al. 2015). In the 1970s, mangrove loss started to occur across new areas outside Java including Kalimantan and Sulawesi, particularly to boost timber production and followed by shrimp pond development in the 1980s. The latter continues as the primary driver of ecosystem mangrove change in Indonesia and in addition to other new frontiers of mangrove loss drivers such as agriculture, coconut and oil palm plantations (Ilman et al. 2016). Likewise, in other natural ecosystems such as primary forests, the loss of mangrove areas can generate negative impacts, such as the loss of biodiversity and carbon storage functions, specifically contributing to significant carbon emissions.

Mangrove ecosystems provide natural long-term carbon storage. It was reported that one of the world's most diverse and well-established mangrove regions in the Indo-Pacific could store approximately 1023 MgC ha^{-1} in their biomass, dead wood and soil carbon pools (Donato et al. 2011). Moreover, Murdiyarso et al. (2015) assessed carbon stocks specifically for 2.9 Mha of Indonesia's mangrove and found a total carbon storage of 3.14 PgC with site-level carbon stocks at 1.083 ± 378 MgC ha^{-1}. With this high carbon stored in Indonesia's mangroves as well as their natural ability to sequester atmospheric carbon, this ecosystem has significant potential and capacity for mitigating climate change. Avoiding more mangrove loss and increasing the spatial area of the mangrove ecosystem will contribute to land-based emission reduction substantially. For example, avoided deforestation in mangroves would reduce emissions equal to 10–31% of estimated annual land use emissions, calculated by the Ministry of Environment Republic of Indonesia for Second National Communication Under the United Nations Framework Convention on Climate Change 2010 (Murdiyarso et al. 2015). To achieve both mangrove conservation and restoration at a national scale, however, better policies and approaches via science-based evidence are necessarily required.

Mangrove conservation in Indonesia is managed and implemented by multiple stakeholders which are composed of government institutions, civil society organizations and private sectors. Multiple regulations associated with mangrove conservation and management were produced to maintain national mangroves, preserve and protect mangroves from further loss and rehabilitate degraded mangroves to increase the national mangrove area (Table 16.16). Furthermore, many community-based mangrove management cases are being implemented across Indonesia. In addition, to raise the awareness of mangrove conservation by the coastal community, these programmes are commonly able to generate some direct cash contribution via ecotourism, mangrove crab farming and silvofisheries (Purwanti et al. 2021). These activities can stimulate the direct benefits of mangroves to local communities while maintaining natural and important mangrove functions in contributing to climate change mitigation and coastal adaptation.

16.8 The Success Story of Mangrove Restoration/Rehabilitation

Mangrove rehabilitation efforts have been performed by the government and by non-governmental organizations (NGOs). Several studies have shown that the success of rehabilitation is influenced by the involvement of local communities and stakeholders in sustainable planning, management, implementation and monitoring (Budiharta et al. 2016; Le et al. 2012). Other studies also show that the success of rehabilitation is influenced by local wisdom (Basyuni et al. 2017a, b), awareness of the importance of the benefits of mangrove forests (Sadono et al. 2020) and socio-economic benefits for residents as factors that can attract local communities to be involved in rehabilitation activities (Le et al. 2012).

Some of the successes of mangrove rehabilitation in Indonesia have had a positive impact on the environment, society and economy of the surrounding community. One of the successful efforts to rehabilitate mangroves is on the Karangsong Beach, Indramayu Regency. Prior to 1983, the area of mangrove on

Table 16.16 Summary of mangrove-related policies in Indonesia (Arifanti 2020)

No	Regulations	Description
1	Law No 5 year 1990	Conservation of Natural Resources and their Ecosystems emphasized on conservation of mangroves as natural resources to ensure the sustainability of its supplies while maintaining and improving the quality of diversity and value
2	Law No 41 year 1999	Forestry then revised in Law No 19 year 2004 states that mangrove management falls under the Department of Forestry
3	Law No 26 year 2007	Spatial Planning states that mangroves belong to one of the protected areas
4	Law No 27 year 2007	Management of Coasts and Small Islands states that coastal area (including mangroves) management falls under the Ministry of Fisheries and Marine Affairs. This law causes overlapping authorities between the Ministry of Forestry and Ministry of Fisheries and Marine Affairs on mangrove management
5	Law No 32 year 2009	Protection and Management of Environment describes the standard criteria for mangrove ecosystem deterioration
6	The Presidential Decree Number 73 year 2012	National Strategy on Mangrove Ecosystem Management laid the basics for the common reference to coordinate and synergize policies, programmes and activities for the management and utilization of Indonesia's mangrove ecosystems
7	The Presidential Decree Number 9 year 2016	One Map as a Guidance for Mangrove Management emphasized the acceleration of the implementation of the One Map Policy at the level of map accuracy of 1: 50,000 scale, to fulfil one map that refers to one geospatial reference, one standard, one database and one geoportal to accelerate national development
8	Regulation of the Coordinating Minister for Economic Affairs No. 4 year 2017	Policy, Strategy, Program, and Performance Indicators of the National Mangrove Ecosystem Management describes the strategy and performance indicators of mangrove ecosystem management where the target of mangrove rehabilitation is set at 1.82 million ha by 2045

this beach reached 45 ha, which was later converted into ponds and other non-mangrove uses. The effort to restore the mangrove ecosystem on this beach was started from 2008 to 2016 by the Kelompok Pantai Lestari (KPL) Group which succeeded in increasing the mangrove area to ±62.30 Ha (Oni et al. 2019). The first year of mangrove rehabilitation at Karangsong Beach covered an area of up to 2.5 ha with three types of mangrove plants, namely, *Rhizophora mucronata*, *R. stylosa* and *R. apiculata*. *Rhizophora* is excellent for rehabilitation activities in Southeast Asian countries because of its ability to protect coastal areas from erosion, waves and storms and because of its ability to hold sediment, easy to propagate (Ellison 2000; Primavera and Esteban 2008) and ease of growth compared to other mangrove species (Idrus et al. 2019).

Over time the rehabilitation activities covered a wider area with an increasing number of plant species, namely, *Avicennia marina*, *A. alba* and *Sonneratia caseolaris*, as well as coastal tree species such as *Terminalia catappa* L., *Casuarina equisetifolia* L. and *Ziziphus mauritiana* Lam. (Gunawan et al. 2017). The existence of mangroves has attracted various animals, including 20 species of birds from 12 families.

Mangrove rehabilitation success also improves the economic benefit of the surrounding community. In Karangsong Beach, mangroves are a tourist destination that provides employment opportunities to the local youth as managers, as well as the officer guarding the gate. In addition, the surrounding economic activity is also growing with the development of stalls and shops. The better the environmental and economic conditions of the community, the more awareness residents have to protect mangroves, especially the stalls owners (Oni et al. 2019).

The success of mangrove rehabilitation was also experienced by Kaliwlingi Village, Brebes Regency, which was designated as a Desa Wisata (tourism village) under the name Desa Wisata Mangrove Sari in 2016. This was after several lessons learnt about the importance of mangroves. Kaliwlingi Village mangroves were converted into shrimp ponds in 1987–1997 with the promise of increasing the communities' economy. However, this activity brought disasters in the form of abrasion and tidal flooding, which resulted in the loss of shrimp ponds (Puspitarini and Laturiuw 2019) and unproductive agricultural land due to seawater intrusion. This caused social impacts as the village children were unable to get an education properly because they were forced to help their parents find fish in the sea (Akbar et al. 2021).

Community awareness of the importance of mangrove forests began in 2007 with an initial rehabilitation of 1.5 ha of mangrove forest, and then 10 years later, the rehabilitation of mangroves reached 250 ha (Akbar et al. 2021). In 2016, to increase the economic value, an area of 40 ha of mangrove was prepared for ecotourism activities. The Mangrove Sari Tourism Village had a brilliant achievement with the number of visitors reaching 209,073 visits in 2017. This level of visits has decreased in subsequent years, the lowest was in 2020 with 52,784 tourists, but this is also predicted to be heavily affected by the Covid-19 pandemic (Akbar et al. 2021).

16.9 Community Participation in Mangrove Management and Its Various Problems: Case studies

The success of mangrove forest management is highly dependent on the active participation of local communities. They have an important role in management because they have local wisdom in preserving mangrove forests and their livelihoods are highly dependent on the existence of sustainable mangrove forests (Eddy et al. 2016). In addition, they have considerable knowledge of the botany and ecology of their forest (Walters et al. 2008). According to Bosire et al. (2008), an important component that affects mangrove restoration in addition to site conditions and monitoring at the ecosystem level is community involvement. The case study in mangrove forest management involving local communities and various problems is in the Air Telang Protected Forest (ATPF) located in Banyuasin Regency, South Sumatra Province, Indonesia (Fig. 16.8).

As a coastal protected forest, ATPF functions to protect the coast from abrasion and storms, capture sediment and prevent seawater intrusion and as a place to live and breed various types of biota. The ATPF area is an area that is strategically located because it is located in the estuary of the Banyuasin River which leads to the Bangka Strait, so it is prone to conversion, especially for seaports. Some parts of the

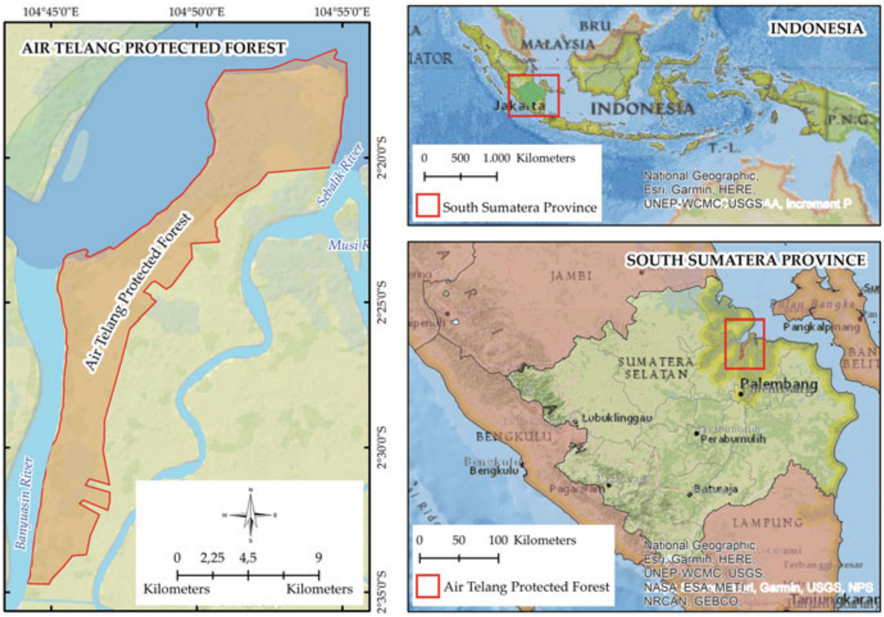

Fig. 16.8 Map of the location of the Air Telang Protected Forest (ATPF) in South Sumatra Province, Indonesia

Fig. 16.9 Land conversion in ATPF by the community in the form of coconut plantations (**a**), ponds (**b**), ports (**c**) and corn plantations (**d**)

ATPF area are currently being converted into ponds, coconut plantations, agriculture, settlements and ports (Fig. 16.9). ATPF has an area of about 12,660 ha, but the remaining primary forest area in 2017 was 6585 ha or about 52% (Eddy et al. 2017), and in 2020, it was only 2936 ha or about 23% (Eddy et al. 2021a). The primary forest was reduced by more than half in just a span of about 3 years (2017–2020). This shows that there is a massive anthropogenic activity in this region.

Meanwhile, the government has developed several infrastructure projects around the ATPF area. Two ports have been built in Tanjung Api-Api (an area adjacent to ATPF), namely, the sea terminal and the ferry terminal. The Tanjung Api-Api area will also be used as a special economic zone (SEZ). The government will also soon build a seaport located in Tanjung Carat which is part of the ATPF area. Community coconut plantations also dominate this area, where around 15% of this area has been converted to coconut plantations and around 50% of this area is a deforested area based on data in 2020 (Eddy et al. 2021a). Anthropogenic influences have changed this area a lot, reducing its function as a protected forest. This is shown from the results of measurements of CO_2 emissions and CO_2 sequestration in the period 2000–2020, where the emissions produced were around 1,981,392 tons CO_2-eq, much larger than sequestration which was only about 53,315 tons CO_2-eq (Eddy et al. 2021b). In addition, *Nypa fruticans* dominates tree-level vegetation in this area

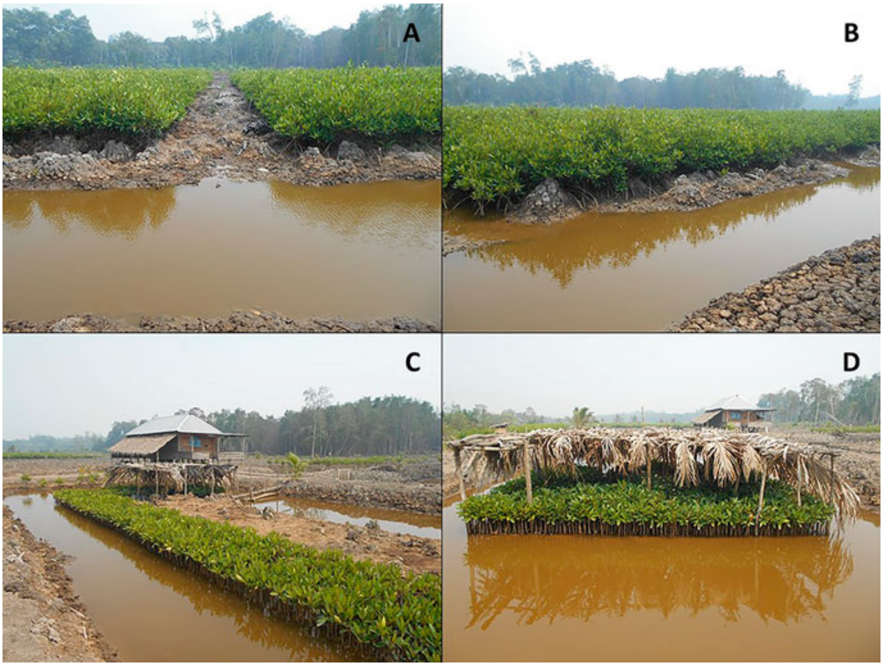

Fig. 16.10 ATPF mangrove forest restoration at the Pancang Besi location, Teluk Payo Village, Banyuasin Regency, South Sumatra, in 2013. The image was taken in 2015; planting results (**a**, **b**) and seedlings of *Rhizophora apiculata* (**c**, **d**)

and invades large parts of the area, which is an indicator of disturbed mangrove forest (Eddy et al. 2019; Eddy and Basyuni 2020).

The government's efforts to preserve ATPF through forest restoration have been carried out several times through the formation of community groups that care about the environment. The restoration programmes that have been carried out include (a) mangrove planting in Tanjung Carat in 2006, (b) mangrove planting in Pancang Besi in Teluk Payo Village in 2013, (c) mangrove planting near Tanjung Api-Api Harbor in 2015 and (d) the establishment of a mangrove park at Tanjung Api-Api Port by LANAL (Navy Base) Palembang in 2019. This restoration activity not only involves the local government but also involves the local community and the TNI (Indonesian National Army). For example, the restoration of mangrove forests in Pancang Besi, Teluk Payo Village (Fig. 16.10), is fully carried out by the community while the government through the Banyuasin District Forestry and Plantation Service only facilitates it. The community in this place planted as many as 120,000 mangrove seedlings with an area of 36 ha which was carried out by 7 farmer groups. However, this effort did not provide maximum results because the land where the mangrove was planted has now been converted by the community for coconut and areca nut plantations. This is due to a land ownership conflict where the mangrove planting land is claimed to belong to the community.

Fig. 16.11 A mangrove park located near the Tanjung Api-Api Port was jointly developed by the local government and LANAL (Navy Base) Palembang

In 2019, the local government in collaboration with LANAL Palembang established a mangrove park near the Tanjung Api-Api Port (Fig. 16.11). This mangrove park makes a positive contribution to public awareness to preserve mangroves. In addition, this mangrove park can be a tourist destination, both for local people and immigrant communities. However, the management is still not optimal, especially related to maintenance because it has not maximally involved the community. For this reason, it is still necessary to maximize the participation of the community and facilitators in this case the government to create a sustainable mangrove park. Another effort that has been made is to encourage pond farmers to implement the silvofishery method, but the community has not experienced significant results from the programme so that until now it has not been going well.

Information from local communities stated that in the ATPF area, there is still a species of Sumatran tiger (*Panthera tigris*) which is a protected species. The presence of migratory birds that are protected at the change of seasons in this area, especially in the Tanjung Carat area, makes this area a conservation priority. The strategic location of the ATPF can also make this area an alternative tourist area and at the same time conserve mangrove forests.

The local community, especially the Bugis community, has local wisdom in maintaining the existence of the existing mangrove forest, namely, by maintaining the mangrove forest on the river coast to resist wind and storms as well as seawater intrusion. In addition, they also built trenches along the coconut plantations. These trenches function as a means of transporting coconuts harvested from the garden and serve to provide freshwater for coconut plants as well as a drainage channel if there is too much water, for example, due to rain.

Currently, local people's sources of income are still limited to the use of natural resources such as forest conversion and capture fisheries. Capture fisheries products are currently starting to decline in line with the condition of the sea which is increasingly polluted with garbage and waste. This is a concern if later fishermen switch professions to become forest encroachers. The lack of economic development policies for local communities is a threat to the existence of ATPF. For this reason, research is needed to support the business of innovative mangrove-based products. This activity is important to divert community businesses to non-land-based sectors to reduce the rate of conversion. In addition, efforts can be made to make mangrove forests a natural tourist attraction which in turn can help increase people's income by not destroying the forest. According to Dat and Yoshino (2013), mangrove restoration programmes can show success if community-based management is carried out in collaboration with the local government.

Weak legal threats against forest encroachers are a threat to the sustainability of ATPF; moreover, the lack of comprehensive monitoring and supervision in the area makes timber looting and forest conversion more rampant. The government should formulate special regulations for protected forest areas with a high level of threat to their existence, such as at ATPF. The government can set various strict rules and severe sanctions for violations that occur in the area through regulations. According to Bosire et al. (2014), strengthening government policies through law enforcement to stop illegal timber extraction is the main action in the effort to conserve mangrove forests. In addition, Sudtongkong and Webb (2008) argue that the success of mangrove forest conservation and management cannot be separated from effective leadership in villages to implement sanctions and resolve conflicts.

In realizing ATPF mangrove sustainability, it is important the community and the government take on several roles. Community participation must play an active role in implementation efforts to restore and maintain natural succession, to maintain local wisdom, to comply with various existing regulations, to play an active role in supervision, to play an active role in various activities to increase community capacity and economy and to care about environmental sustainability. The important role of the government is to establish policies for sustainable natural succession restoration and maintenance programmes that involve the community actively, enforce strict laws against forest destruction, develop clear zoning policies and their implementation, facilitate capacity building and the community's economy by involving various stakeholders and formulate a strategic plan for the management of ATPF in an integrated manner.

16.10 Concluding Remarks

Despite being one of the world's most vulnerable ecosystems, the mangrove ecosystem is one of the most productive, including in Indonesia. Indonesia hosts the largest mangrove forest area in the world consisting of 2.7 m ha in 2020 and supports coastal communities with ecosystem services and thus increasing the roles for livelihoods of communities. Community-based mangrove management cases are being implemented across Indonesia. In addition, to raise the awareness of mangrove conservation by the coastal communities, these programmes can generate some direct contribution via ecotourism, mangrove crab farming and silvofisheries. These activities can stimulate the direct benefits of mangroves to local communities while maintaining natural and important mangrove functions in contributing to climate change mitigation and coastal adaptation.

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Chapter 17
Mangroves Sustaining Biodiversity, Local Livelihoods, Blue Carbon, and Local Resilience in Verde Island Passage in Luzon, Philippines

Dixon T. Gevaña, Carlos Mico M. Villanueva, Josephine E. Garcia, and Leni D. Camacho

Abstract The Verde Island Passage (VIP) is a world-renowned center for shorefish biodiversity. Mangrove forests that commonly thrive along its coasts play a vital role of protecting the vast coral reef habitats of which many organisms and local livelihoods are intimately dependent. This chapter describes how mangroves sustain biodiversity, local livelihoods, and blue carbon stocks of VIP. It also expounds on why keeping a healthy mangrove cover can also enhance local resilience to climate change. Mangrove deforestation and degradation were observed to be pressing as seen in the decline of dense mangrove vegetations between the years 2005 and 2020. If not properly addressed, this will entail serious negative impacts on the passage's ability to provide vital ecosystem goods and services. To overcome this, several recommendations were identified for the local stakeholders to pursue. These include the following:

1. Adoption of collaborative management approach through conservation projects and programs that will encourage partnership among the local government, local communities and other coastal stakeholders.
2. Development of an integrated and comprehensive coastal management plan where mangrove conservation is assured in the proposed budget, plans, and programs.
3. Strict enforcement of environmental laws such as those that are related to banning mangrove cutting and proper solid and wet waste management.
4. Science-based forest rehabilitation of degraded mangrove areas (particularly abandoned fishponds) that adhere to proper ecological site species suitability matching.
5. Harnessing the economic potential of mangrove blue carbon through developing carbon offset projects.

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Keywords Biodiversity · Carbon stock · Climate change · Ecosystem services · Livelihood · Resilience

17.1 Introduction

The Philippines is endowed with rich natural resources. It is one of the 18 mega-biodiverse countries of the world and ranks fifth in the number of plant species. It also maintains 5% of the world's flora. High species endemism also describes its tropical ecosystem, with at least 25 genera of plants and 49% of terrestrial wildlife. The country is regarded as one of the world's centers for marine biodiversity being situated within the Sulu-Sulawesi Seascape.

Unfortunately, as habitats continue to degrade, the Philippines is also considered as a biodiversity hotspot. It has about 42 species of land mammals, 127 species of birds, 24 species of reptiles, and 14 species of amphibians that are listed to be threatened. Similar to other countries in the tropics, natural habitats became at higher risk of degradation because of climate change. Climate-related hazards such as storm, flood, drought, and landslide are causing much damage to natural ecosystems. Unregulated human activities such as logging, overfishing, and forest conversion to other land uses (e.g., agricultural farms, settlements, and industries) have further exacerbated habitat degradation (Cabral et al. 2014). Among the most vulnerable ecosystems are the mangrove forests.

Mangroves are generally described as true ecotone of land and sea. They have unique flora that is comprised of salt-tolerant plants belonging to 9 orders, 20 families, 27 genera, and roughly 70 species. They also thrive within the tropical and subtropical regions (32° N to 32° S) and delimited major ocean currents with 20 °C isotherm seawater during the winter season (Alongi 2010). Mangrove plants are also adaptive to many natural stressors such as high temperature, high salinity, anaerobic sediments, and extreme tides. However, as they are sensitive to many climate hazards, they have become more degraded because of the anthropogenic disturbances such as land use conversion to aquaculture ponds, oil palm plantation, and cutting for fuelwood and tanbark extraction (FAO 2007). In some countries, mangrove stands are already at the edge of complete collapse (Gevaña et al. 2015). About half of the world's mangrove forests was lost over the past half century (FAO 2007). This reflects the immense damage to the vital ecological and economic benefits they provide. Just within the three decades time (1990–2020), the planet has lost as much as 1.04 million ha.

The same downtrend of mangrove cover was noted for the Philippines. About 40% of mangroves was lost from their earliest record of around 500,000 ha during the nineteenth century (Garcia et al. 2014; Gevaña et al. 2018). Land use conversion to aquaculture ponds was the prominent cause of their deforestation (Primavera 2000). Currently, the country sustains around 303,000 ha of mangrove cover. The protection of this remaining vegetation is critical as the country shelters half of the world's mangrove plant species with 35–44 major and minor mangrove species belonging to 14 families (Primavera 2000).

Moreover, deforestation hampers the mangrove ecosystem's ability to mitigate climate change and deliver its ecosystem services (Camacho et al. 2011). Forest cover loss entails the decline of forest biomass which could have been instrumental in sequestering and storing large amounts of carbon from the atmosphere. A healthy mangrove stand can store as much as 3.7 gigagrams of carbon dioxide per hectare (Gg CO_2 ha^{-1}) (Donato et al. 2011), a value that is likely to be triple the capacity of other terrestrial forest ecosystems in the tropics. In addition, a well-protected mangrove supports many ecosystem services such as those that provide for human needs such as food, shelter, fuelwood, and livelihoods.

This chapter generally aims to provide the foundation for prioritizing mangrove conservation in the Philippines to support biodiversity, climate change mitigation, and local livelihoods. It takes Verde Island Passage (VIP) of Luzon, Philippines, as its case, being one of the world's richest marine biodiversity corridors that is under threat of degradation. Several recommendations for its conservation were also listed.

17.2 Study Site

Verde Island Passage (VIP) can be found in Luzon Island, Philippines (Fig. 17.1). It is surrounded by five major provinces, namely, (a) Batangas, (b) Marinduque, (c) Romblon, and (d) Oriental and Occidental Mindoro. This corridor shelters the

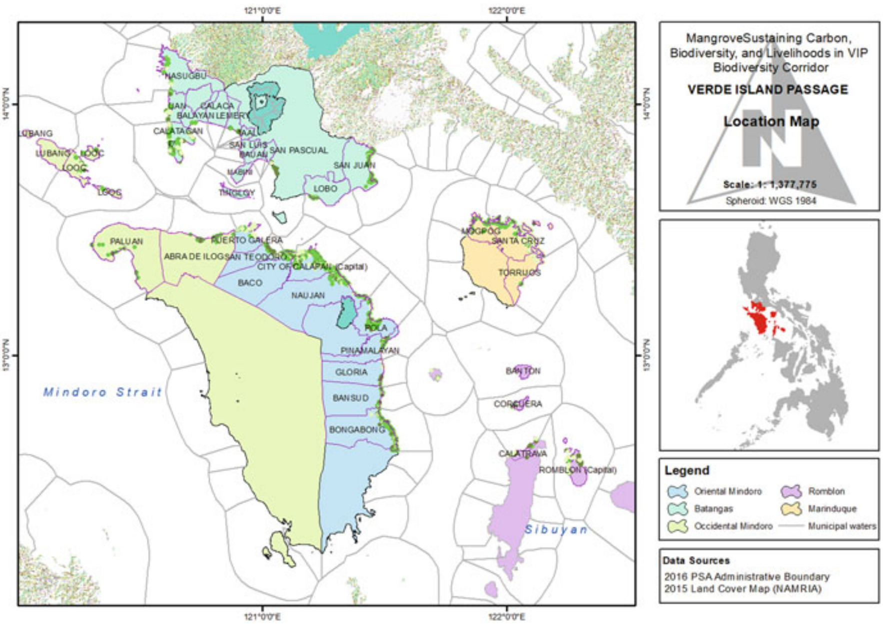

Fig. 17.1 Location map of Verde Island Passage

Fig. 17.2 Common mangrove vegetation along Verde Island Passage (Photos: DT.Gevaña)

highest concentration of marine fish species per unit area. It is known as the *center of the center* of the world's marine shorefish diversity with as much as 1736 marine species within just a 10-km area (PAWB–DENR 2009). Its coral reef system is also remarkable which spans to 8000 hectares. The study of Carpenter and Springer (2005) reported that this biodiversity rich site is facing serious anthropogenic threats such as illegal fishing and mangrove deforestation. In 2006, a conservation policy through Executive Order No. 578 was then enacted to protect this site (PAWB–DENR 2009).

Fishing is the main source of livelihood for many surrounding coastal communities. Mangroves maintain this livelihood by providing a nursing and spawning ground for diverse fishes. By estimate, VIP's mangroves cover around 4802 ha. Some of the dominant floristic genera that can be found here include *Avicennia*, *Bruguiera*, *Ceriops*, *Excoecaria*, *Rhizophora*, *Aegiceras*, and *Sonneratia* (Fig. 17.2). There are as many as 26 different mangrove species and mangrove associates present in this passage (Salmo III et al. 2015).

17.3 State of Mangrove Cover in VIP

Map digitization and Normalized Difference Vegetation Index (NDVI) analyses were done to describe the mangrove cover changes in VIP. Mangrove areas were first identified using available land cover maps from the National Mapping and Resource Information Authority (NAMRIA) from the years 2003, 2010, to 2015. Maps were then projected to the geographic coordinate system of WGS_1984 using

ArcGIS (V.10.3) software. In map digitization, Google Earth Pro Software was used to properly select the mangrove sites based on the available satellite imageries. The manual digitization involved the point-to-point tracing of mangrove cover features to generate polygons. To further validate and verify the reliability of the digital output, the 2019 mangrove cover map generated by Baloloy et al. (2020) was used as a reference.

A number of Landsat data imageries with a combination of medium resolution (20 m/px) and NDVI bands for the years 2005 and 2020 were acquired online from a GIS-based network called *LandViewer*. *LandViewer* is an online software which offers the latest and high-quality satellite observation imageries along with smart analytical tools. Similar to Google Earth Pro, satellite scenes from *LandViewer* are free and readily available; however, it is limited to ten images on a daily basis. In selecting Landsat scenes, imageries with the level of cloudiness not exceeding 10% were considered to avoid unnecessary errors in the analysis. Further, the acquired Landsat scenes were in the format of a GeoTIFF file to be later processed in ArcGIS.

The mangrove cover change at a specific location was then determined by rendering map features from the processed NDVI map using the prior digitized mangrove maps. Results of mangrove cover change analysis revealed three different vegetation types, namely, dense (60–100% vegetation cover), sparse (30–59% vegetation cover), and bare (0–29% vegetation cover).

Figure 17.3 summarizes the mangrove vegetation cover of VIP for the two periods: year 2005 and year 2020. Of the current 4802 ha of mangrove forest today, dense mangroves constitute only 22.3% (1073 ha). This is 56% lower than the dense cover in 2005 which was 2438 ha, which implies a decrease in the areas that are covered by healthy and well-vegetated mangroves. Apparently, the area of sparsely covered mangroves showed an increase from 1125 ha (in 2005) to 2906 ha (in 2020). This suggests that a considerable area of dense mangrove became sparse,

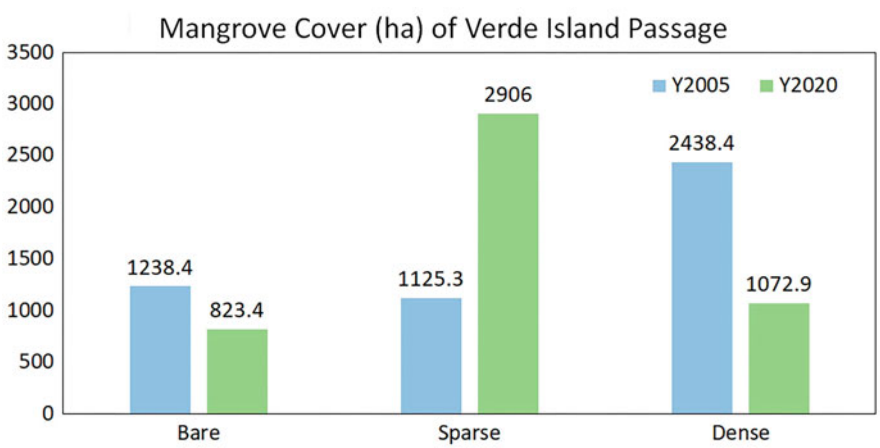

Fig. 17.3 Mangrove area (ha) of Verde Island Passage for years 2005 and 2020 based on vegetation cover types

Fig. 17.4 Major threats to mangroves of Verde Island Passage (Photos: DT.Gevaña)

Table 17.1 Mangrove cover change in the provinces covered by Verde Island Passage

Province	Year	NDVI range		
		Bare	Sparse	Dense
Batangas	2005	225.0	361.3	12.7
	2020	54.6	474.4	70.0
Marinduque	2005	465.9	379.0	1850.6
	2020	531.9	1424.1	739.6
Occidental Mindoro	2005	67.6	16.9	16.1
	2020	16.8	67.8	16.0
Oriental Mindoro	2005	473.8	357.8	513.7
	2020	209.6	919.9	215.9
Romblon	2005	6.1	10.3	45.3
	2020	10.5	19.8	31.4

which can be attributed to some anthropogenic activities that contributed to partial deforestation or degradation. Land use conversion to fishponds, industries, rice fields, and settlement areas are a few of the possible causes of mangrove deforestation and degradation (Fig. 17.4). In view of bare mangrove areas, a decrease was observed between the years 2005 and 2020, with 1238 ha and 823 ha, respectively. This change can be somehow attributed to mangrove rehabilitation and protection activities that were done in these years.

Table 17.1 summarizes the mangrove cover distribution among the provinces covered by VIP. In Batangas, dense mangrove cover was observed to have increased from 12.7 ha to 70 ha indicating both rehabilitation and protection efforts that are being done on this site. This improvement in cover can be also observed in the decrease in open or bare areas (from 225 ha to 54.6 ha) which became sparsely vegetated in 2020. In the case of Marinduque, there is an evident loss in the dense mangrove cover and an increase in the open areas. About 60% of dense mangroves in 2005 were lost with only about 740 ha left in 2020. This decline had led to the increase in the sparse areas by about 1045 ha. Moreover, the complementing changes between the decrease in dense mangroves and the increase in open areas suggest that the clearing of mangroves may have occurred previously between 2005 and 2020. Similar to Marinduque, the provinces of Occidental and Oriental Mindoro and Romblon have all experienced a decline in dense mangrove cover. In Oriental Mindoro, about 300 ha of dense mangroves were lost in a span of 15 years which resulted in almost 600 ha increased in the sparse areas. But positively, about 260 ha from the bare cover have now been sparsely vegetated. On the other hand, Romblon follows a similar trend with that of Marinduque. A decrease of almost 15 ha was observed in the dense mangrove from 2005 to 2020. Following this trend is the loss of dense mangrove cover which led to the opening of about 4 ha in the bare areas and 9 ha as sparse. In the province of Occidental Mindoro, there is but a very small decrease in the dense mangrove cover by only 0.1 ha. In line with this, there is a noticeable increase in the partially vegetated areas leaving only about 17 ha of areas still left open.

17.4 Mangrove Sustaining Marine Biodiversity

The observed changes in mangrove cover have implications on the quality of biodiversity in VIP. The increase of some dense mangrove areas and the reduction of bare/open sites should be sustained to effectively protect the rich marine biodiversity of this passage particularly the reefs. By estimate, VIP's reef area is approximately 8100 hectares and is deemed as one of the most diverse in the world and the richest in the Coral Triangle Region. Coral reefs serve as habitat and feeding grounds for small and young fishes. According to Bell and Galzin (1984), fish species richness is affected by coral cover area. The greater the coral cover, the larger the feeding ground and habitat for juvenile fishes. However, degradation of coral reef in VIP is inevitable due to several natural stressors like strong waves, increase in sea level temperature, weather condition changes, and man-made threats like overfishing and pollution. Mangroves, on the other hand, may not directly affect coral reef area but contribute in a unique manner. Mangroves promote the increase in reef fish biomass; this includes several fish species including coral feeding fish species or corallivores. These corallivore fish species, as the name may suggest, reduce portions of corals as they feed on them. However, coral reefs regenerate in time, and according to Bellwood et al. (2003), some coral feeding species may promote reef strengthening or hardening through a process called bio-erosion. Today, around 25% of the total reef area in VIP are live corals. On a healthy reef, coral feeding causes minimal impacts to corals; however, it may affect greatly when combined with numerous threats (Cole et al. 2008). Coral reef degradation in VIP is caused by a number of threats from illegal extraction of corals, destructive fishing methods, unsustainable culture practices, marine-based pollution, and mangrove degradation (PAWB–DENR 2009). Aside from these, corals are also vulnerable to high sedimentation (Brown and Ogden 1993; Larsen and Webb 2009; Anthony 2006). Weber et al. (2012) specified that bleaching or mortality of corals can occur upon contact with sediment runoff from uplands. Mangroves, on the other hand, provide coral protection from sediment runoff (Miththapala 2008). Sediments from the upland tend to accumulate and are later trapped by complex root systems of mangroves after sediment runoff preventing soil erosion and coral sedimentation.

Mangroves of VIP also improve the fish and marine life populations, by acting as breeding grounds providing habitat and refuge to small fishes away from their predators (Laegdsgaard and Johnson 2001; Rogers and Mumby 2019) as well as food in the form of decomposed *detritus* or fallen leaves and wood materials from the mangroves. This relationship promotes an increase in mangrove area productivity and improves fish populations (Hutchison et al. 2014). Small fishes tend to hide in small cracks of corals and small spaces in mangroves to seek shelter away from predators. The decrease in predatory-associated loss of fish populations enables important fish species to thrive and increase in number. For instance, Mumby et al. (2004) stressed that because of some mangrove clearing in the Atlantic, the rainbow parrotfish (*Scarus guacamania*) had experienced severe extinction on a local scale.

17.5 Mangroves Sustaining Coastal Livelihoods

With mangroves being able to sustain marine life forms, the growth in the population of many commercial fish species and crustaceans has encouraged commercial fishing in VIP (Fig. 17.5). However, many have been practicing harmful methods that are

Fig. 17.5 Mangrove-dependent livelihoods: (**a**) fishing, (**b**) ecotourism enterprise (Photo: DT Gevaña and I. Barraquias)

illegal and caused overfishing. Along with this, VIP is faced with many other challenges which lead to its degradation; these are unsustainable use of resources, coastal development, pollution and contamination, disaster-induced damages, and the effects of climate change (Switzer 2015). With that said, the identification and establishment of marine-protected areas (MPAs) have become an essential factor in alleviating said challenges including harmful fishing activities (Horigue et al. 2015; Sollestre et al. 2018). The goal of establishing a protected area is to promote biodiversity conservation and sustain the related ecosystem services (Margules and Pressey 2000). In addition, MPA management intimately involves the locals in its implementation. The establishment of the Batangas MPAs has opened income opportunities for the locals as they were deputized to be members of *Bantay Dagat* or sea wardens who receive some honorarium for patrolling and monitoring the coasts including the mangrove areas. Vanderklift et al. (2019) asserted that the participation of the local people is extremely vital for conservation and management efforts. From a case study in Vietnam by ELAN (2011), the importance of a community-based coastal management approach was stressed to encourage sustainable management, reduce disaster-induced vulnerability, and promote livelihoods for the coastal communities. For instance, the community-based mangrove management project in the northern part of VIP (in Calatagan, Batangas) was mentioned to be a successful endeavor between the People's Organization of fisherfolks and the government to bring back the mangrove forest. According to Buncag et al. (2019), this project had brought an improvement to fish and crustacean catch, hence more opportunities for local income.

In Silonay, Calapan City, Oriental Mindoro, the collaboratively managed ecopark by the People's Organization and local government unit is sustainably providing additional income to the local community through the ecotourism enterprise (Fig. 17.5). This park also organizes educational and recreational activities to raise local awareness on mangrove conservation. Other popular mangrove ecoparks in VIP include Puerto Galera Mangrove and Ecotourism Area (in Oriental Mindoro), Calatagan Mangrove Forest Conservation Park (in Calatagan, Batangas), and Olo-olo Mangrove Forest and Ecopark (in Lobo, Batangas). Studies suggest that the establishments of mangrove ecotourism spots have been extremely significant to locals due to many opportunities to earn and cooperate (Bansil et al. 2015; Diona et al. 2016).

17.6 Mangroves Sustaining Blue Carbon

Blue carbon pertains to the carbon stock that is stored by coastal marine vegetations including mangrove forests (Gevaña and Im 2016). Mangrove vegetation and sediment sequester store vast amount of carbon dioxide from the atmosphere. The bulk of the carbon stock is usually embedded in the sediments. Blue carbon stocks of VIP's mangroves are expected to be high since the vegetation is generally dense with a healthy sediment condition beneath. Table 17.2 shows the reported carbon stock

Table 17.2 Carbon estimation in Verde Island Passage from related studies

Province	Vegetation type	Mangrove area (ha)	Est C stock (Mg C ha^{-1})	Carbon pool	Reference
Batangas (San Juan)	Natural, Avicennia stand	610.9	125.8	Vegetation	Gevaña et al. (2008)
Batangas (San Juan	Natural, Rhizophora stand	15	115.5	Vegetation	Gevaña and Pampolina (2009)
Batangas (Batangas City)	Natural, mixed species	26.5	203.9 to 466.5	Vegetation + sediment	USAID (2017)
Batangas (Calatagan)	Natural, mixed species	357.4	625.9	Vegetation + sediment	Salmo III (2019)
Oriental Mindoro (Calapan City)	Natural, mixed spp.	2391.70	579.7	Vegetation + sediment	Salmo III (2019)
Marinduque (Sta. Cruz)	Natural, mixed spp.	3197.6	689.6	Vegetation + sediment	Salmo III (2019)
Romblon (Looc)	Natural, mixed spp.	1114.9	599.4	Vegetation + sediment	Salmo III (2019)

Table 17.3 Potential aboveground blue carbon stock of Verde Island Passage

Province	Bare	Sparse	Dense
Batangas	0.7	29.8	8.8
Marinduque	8.9	96.6	11.8
Occidental Mindoro	0.2	4.3	2.0
Oriental Mindoro	2.6	57.9	27.2
Romblon	0.1	1.3	4.0
Total	*12.6*	*189.8*	*53.8*

estimates. In San Juan (in Batangas), Gevaña et al. (2008) reported about 125 Mg C ha^{-1} in the vegetation pool. In an adjacent site of San Juan, the vegetation of a *Rhizophora*-dominated stand has about 84.5 Mg C ha^{-1} (Gevaña and Pampolina 2009). Natural mangroves of Batangas City contain as much as 466.5 Mg C ha^{-1} (USAID 2017). Of this, the sediment contributes the bigger bulk with around 71%. Salmo III (2019) also reported huge estimates for (1) Calatagan, Batangas (625.9 Mg C ha^{-1}), (2) Calapan City, Oriental Mindoro (549 Mg C ha^{-1}), (3) Sta. Cruz, Marinduque (689.6 Mg C ha^{-1}), and (4) Looc, Romblon (599.4 Mg C ha^{-1}). Bulk (at least 80%) of these estimates are found in the sediment.

Based on the current mangrove cover values that are presented in Table 17.1 and the carbon stock estimates in Table 17.2, the potential aboveground/vegetation blue carbon stock of VIP's mangroves could be at least 256 Gg C (Table 17.3). This is a conservative estimate since sediment carbon is not yet accounted for. The largest share (74%) of this stock is from the sparse/partially vegetated areas with as much as 189.8 Gg C. These are most common in the provinces of Marinduque and Oriental

Mindoro. If the sites are seriously rehabilitated and protected, greater blue carbon stocks can be expected. If valued as a tradable commodity in the voluntary carbon market at USD 4.3 per ton of CO_2 (Donofrio et al. 2020), the potential worth of VIP's mangrove vegetation is as much as USD 3.94 million, an ecosystem service that is worth conserving indeed.

17.7 Mangrove Sustaining Local Resilience

Coastal communities that keep healthy mangroves are more resilient to climate change's catastrophic impacts, such as storm surges, and incur fewer losses as a result. Hence, a long-term conservation of mangroves and other coastal ecosystems in VIP should be pursued to prevent the most devastating effects of climate change. Enhancing the coastal community's resilience requires an optimal balance among community development, coastal management, and disaster management (Fig. 17.6). Community development provides the enabling governance, socioeconomic, and cultural conditions for resilience (Center for Community Enterprise 2000; Gevaña et al. 2019, 2021). Coastal management provides the framework for managing human uses of coastal resources, including mangroves and the coastal zone in order to maintain environmental and ecosystem resilience (White et al. 2005; Chua 1998). Lastly, disaster management focuses on preparedness, response, recovery, and mitigation to reduce human and structural losses from disaster events (Abarquez and Murshed 2004).

Mangrove conservation in VIP will be successful if the socio-ecological well-being of coastal communities will be met. In a small coastal community in Infanta,

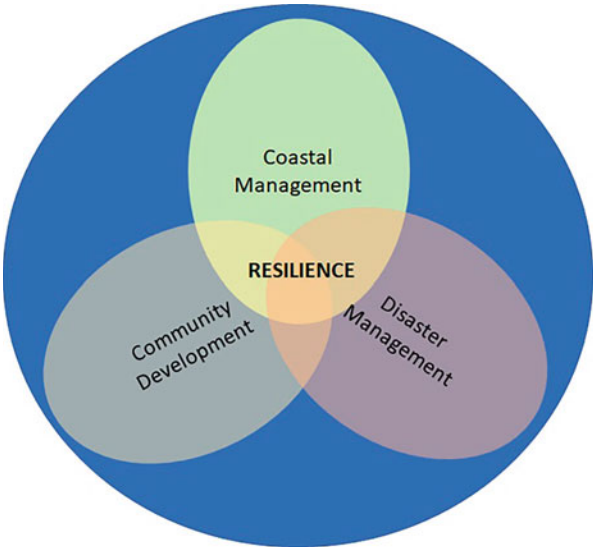

Fig. 17.6 Resilience as an integrating framework for community development, coastal management, and disaster management domains (Source: U.S. Indian Ocean Tsunami Warning System Program 2007; Gevaña et al. 2021)

Quezon, Philippines, Gevaña et al. (2021) emphasized the importance of pursuing collaborative mangrove management to promote local resilience and inclusive growth of mangrove stakeholders. This approach requires the following:

1. Local stakeholders should understand the importance of mangrove conservation as an effective climate change adaptation strategy. A good mangrove cover will lessen the community's vulnerability to the impacts of typhoons and floods, while sustaining the ecosystem services such as those that provide food and livelihood.
2. Active local participation should be observed in rehabilitation projects. This will create additional income sources for the local community and may also strengthen their sense of stewardship and commitment toward protecting the mangroves they have planted.
3. Government must commit to assist the local community on their mangrove conservation efforts. This should be expressed in terms of providing them livelihood projects, enforcing mangrove protection policies, and pursuing other policy improvements that complement the community's interest in conserving mangroves. Such a sense of constituent governance will further improve local people's trust and support for the government.

17.8 Summary and Recommendations

Mangroves of Verde Island Passage play a vital role in sustaining the rich marine biodiversity and the associated livelihoods and ecosystem services. Furthermore, the huge blue carbon stock estimates suggest the need for their immediate and sincere conservation to ensure such vital climate change mitigation role. Despite the policies that were put in place to protect this passage, mangrove deforestation and degradation remains serious as seen in the decline of areas covered by dense vegetation. Such a downtrend implies the negative impacts on biodiversity, marine-based livelihoods, blue carbon sequestration function, and local resilience to climate change impacts. There is a need to overcome the anthropogenic pressures that cause these problems. Some possible ways to move forward are the following:

- *Strengthening partnership among coastal stakeholders through collaborative management approach.* Local government, local communities, and other coastal stakeholders should pursue collaborative mangrove conservation. This entails the development of a single, integrated, and comprehensive coastal management plan for the whole passage, of which the various local government agencies, civil society groups, People's Organizations, and other stakeholders will be intimately involved in the planning and program implementations.
- *Strict enforcement of environmental laws.* Mangrove deforestation and degradation problems in the study sites are reflective of the need for strict enforcement of environmental laws such as the Republic Act 7161 (which bans mangrove cutting) and Republic Act 9003 (proper management of solid wastes). Correspondingly, the conversion of mangroves to industrial land uses was also noted as

an apparent issue which is indicative of limited compliance of industries to the mitigation plans that are stipulated in their Environmental Impact Assessment/ Studies documents. Addressing these limitations would require crafting local policies, enforcement of existing ones, and institutionalization of individuals/ groups from the local government and nongovernment sectors (who will monitor compliance).

- *Implementing science-based mangrove rehabilitation.* In pursuing coastal rehabilitation of degraded mangrove sites, plans and efforts should aim at improving floristic diversity and reviving important ecosystem services such as carbon sequestration. Mixed species and zonal planting approach, which adheres to ecological site species suitability matching, must be followed.
- *Harnessing the economic potential of mangrove blue carbon*. The huge potential economic value of mangrove carbon stock and sustained mangrove degradation problem suggests the need to explore incentive-based conservation programs such as carbon offset projects (e.g., REDD Plus). More studies to accurately account the passage's blue carbon stocks will be helpful to provide references for potential carbon projects in the future.

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Chapter 18
Mangroves of Japan

Tomomi Inoue, Ayato Kohzu, Yasuaki Akaji, Shingo Miura, Shigeyuki Baba, Nozomi Oshiro, Mio Kezuka, Mami Kainuma, Harumi Tokuoka, and Tohru Naruse

Abstract The mangroves of Japan are at the northern limit of their distribution in the Indo-Pacific region; Kamino River of Hioki City (31°37′N) may in fact be the northernmost limit of mangroves in the world. Mangroves are found only in two southern prefectures, namely, Kagoshima and Okinawa. The total area of mangroves in Japan is 870 ha, less than 0.01% of the country's total forest area, but they are protected and increasing in area and important for tourism.

Eleven mangrove species occur in Okinawa Prefecture and four species occur in Kagoshima Prefecture. In the first case study, the contents of mineral nutrients in mangrove rivers and in the leaves of *Bruguiera gymnorhiza* and *Rhizophora stylosa*, on Ishigaki and Iriomote Islands, were measured. The second case study describes the faunal, distributional, and ecological features of decapod crustaceans inhabiting mangrove environments in Japan. Tourism and beach cleaning activities on Iriomote Island are components of the third case study.

Note: General Description was written by Nozomi Oshiro, Mio Kezuka and Mami Kainuma; Case study on mineral nutrients in the leaves of two mangrove species was by Tomomi Inoue, Ayato Kohzu, Yasuaki Akaji, Shingo Miura and Shigeyuki Baba; Case study on decapod crustaceans inhabiting mangrove ecosystems was by Tohru Naruse; Case study on tourism and beach cleaning on Iriomote Island was by Nozomi Oshiro, Mio Kezuka and Harumi Tokuoka.

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Keywords Nansei Islands · Iriomote Island · Mineral nutrients · Decapod crustaceans · Tourism · Beach cleaning

18.1 General Description

Japan is an island country stretching 3000 km from the north to south, between latitudes of 20°25′31″N and 45°33′26″N (Geospatial Information Authority of Japan (GIS) 2019), and has a land area of ~378,000 km^2 (Geospatial Information Authority of Japan (GIS) 2021). According to the Forestry Agency of Japan (2019), ~67% of the total land area of the country is covered with forests. Japan has a wide variety of forests. Forests in the northernmost area are boreal forests dominated by conifers such as *Abies sachalinensis* and *Picea jezoensis*. Most of the northern area are temperate forests covered with deciduous broad-leaved trees. Forests of the central part of Japan are laurel forests dominated by evergreen broad-leaved trees. The Nansei Islands are a linear chain of islands in the southernmost part of Japan. They consist of Iriomote, Ishigaki, and Miyako in the south; Okinawa, Tokunoshima, and Amami in the center; and Tanegashima and Yakushima in the north (Fig. 18.1). Satsuma Peninsula and Osumi Peninsula are not included as part of the Nansei Islands. These islands are dominated by evergreen broad-leaved trees in the hills and by mangroves along the shores.

Mangroves of Japan are at the northern limit of their distribution in the Indo-Pacific region (Miyawaki 1986). They are distributed only in two southern prefectures, namely, Kagoshima and Okinawa Prefectures. The total area of mangroves in Japan is 744 ha (Spalding et al. 2010), which is about 0.003% of the country's total forest area.

18.1.1 Mangroves in Okinawa Prefecture

Okinawa Prefecture, which is the southernmost prefecture of Japan, has more mangroves in terms of distribution area and species diversity. Table 18.1 shows mangrove species on the four major islands of Okinawa Prefecture, namely, Okinawa (26°28′N), Miyako (24°46′N), Ishigaki (24°24′N), and Iriomote (24°20′N). Locations of these islands are shown in Fig. 18.1. There are many other smaller islands with mangroves, but they are not shown in the Fig. 18.1.

Iriomote is the largest area of mangroves in Japan. The island has more than 30 mangrove species including the associates. The Urauchi River, which flows through Iriomote, is the longest river in Okinawa Prefecture. The river has the largest number of fish species with more than 407 species including 23 unidentified species and 43 endangered ones. Most of these fishes communicate between the seawater zone and brackish water zone (Suzuki 2016).

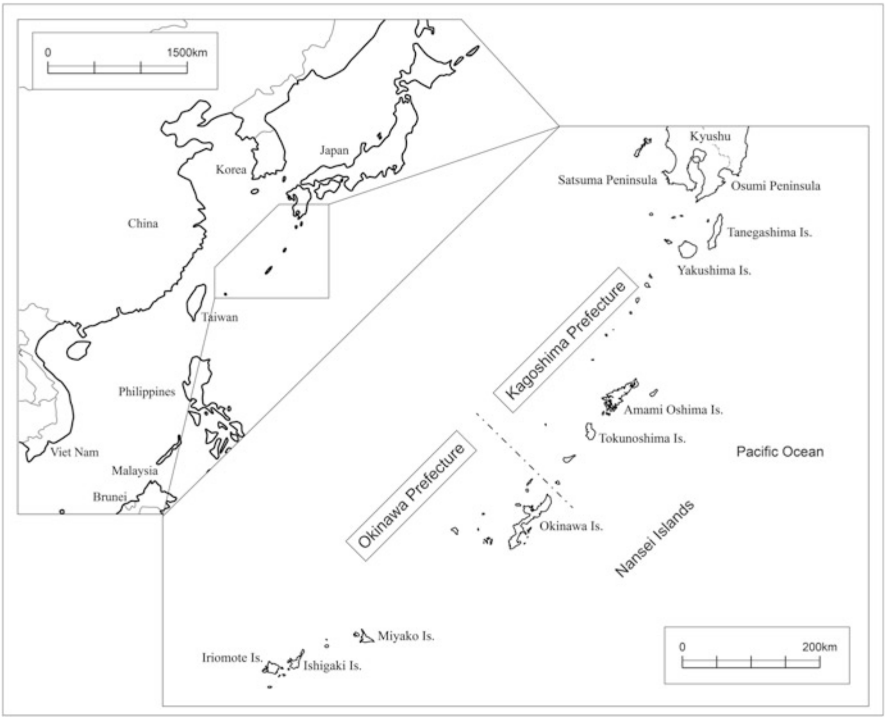

Fig. 18.1 Locations of Okinawa Prefecture, Kagoshima Prefecture, and Nansei Islands. The Nansei Islands do not include Satsuma and Osumi Peninsulas

Table 18.1 List of mangrove species on four major islands of Okinawa Prefecture

Family name	Species name	Ishigaki	Iriomote	Miyako	Okinawa
Major component					
Avicenniaceae	*Avicennia marina* (Forssk.) Vierh.	△	✓	✓	
Combretaceae	*Lumnitzera racemosa* Willd.	✓	✓	✓	✓
Arecaceae	*Nypa fruticans* Wurmb		✓		
Rhizophoraceae	*Bruguiera gymnorhiza* (L.) Lam.	✓	✓	✓	✓
Rhizophoraceae	*Kandelia obovata* Shueu, Liu et Yang	✓	✓	✓	✓
Rhizophoraceae	*Rhizophora stylosa* Griff.	✓	✓	✓	✓
Sonneratiaceae	*Sonneratia alba* Sm.	✓	✓		
Minor component					
Euphorbiaceae	*Excoecaria agallocha* L.	✓	✓	✓	✓
Lythraceae	*Pemphis acidula* J. R.Forst et G.Forst	✓	✓	✓	✓
Pteridaceae	*Acrostichum aureum* L.	✓	✓		
Sterculiaceae	*Heritiera littoralis* Aiton	✓	✓	✓	✓

✓ Naturally distributed, and △ introduced

Table 18.2 Seven major mangrove locations in Kagoshima Prefecture

Location and latitude	Species name	Estimated extent (ha)
Satsuma Peninsula Kamino River in Hioki City (31°37′N)	*K. obovata*	<0.1
Satsuma Peninsula Oura River in Minamisatsuma City (31°23′N)	*K. obovata*	<0.2
Satsuma Peninsula Kiire Town in Kagoshima City (31°19′N)	*K. obovata*	1.0
Tanegashima Island Oura River (30°26′N)	*K. obovata*	~30
Yakushima Island Kurio River (30°16′N)	*K. obovata*	<0.1
Tokunoshima Island (27°50′N)	*K. obovata*	~4.0
Amami Oshima Island Sumiyo River (28°15'N)	*K. obovata* *B. gymnorhiza* *H. littoralis* *E. agallocha*	~45

Sources: Baba and Kitamura (1999), Baba and Nagashima (2017), Spalding et al. (2010), Terada (2017) and Baba, personal communication in 2021

The latitudes shown are at the center of each mangrove location. There are more than one location of mangroves on Tanegashima Island and on Amami Oshima Island, but they are not included in the table. The extent of ~30 ha at Oura River and ~45 ha at Sumiyo River is the total for mangroves on the two islands

18.1.2 Mangroves in Kagoshima Prefecture

In Kagoshima Prefecture, mangroves are distributed in nearly 30 locations, some are in very small patches. There are seven main locations (Table 18.2). Three of the locations are in the Satsuma Peninsula, namely, Kamino River in Hioki City, Oura River in Minamisatsuma City, and Kiire Town in Kagoshima City. The remaining four areas are on the islands of Tanegashima, Yakushima, Tokunoshima, and Amami Oshima.

Kandelia obovata is monospecific or the sole species in all locations. Only in the Sumiyo River of Amami Oshima Island where *Bruguiera gymnorhiza*, *Heritiera littoralis* and *Excoecaria agallocha* are also found.

Mangrove communities in Kiire Town of Kagoshima City in the Satsuma Peninsula have been designated as Special Natural Monument. Most scientific papers have cited Kiire Town (31°19′N) as the northern limit of mangrove natural distribution of Japan, but the Kamino River of Hioki City (31°37′N) may in fact be the northernmost limit of mangroves in the world. Mangroves in most of these areas are stunted stands of less than 2–3 m in height and are purely *K. obovata*.

18.1.3 Extent of Mangroves in Okinawa Prefecture

To understand distribution of major mangrove community in Okinawa Prefecture, ISME compared aerial photographs taken in 1977 with 58 locations on 5 islands of Okinawa Prefecture, namely, Okinawa, Miyako, Ishigaki, Iriomote, and Kohama.

Table 18.3 Extent of mangroves in 1977 and from 1993 to 2001

Name of islands	1977 (ha)	1993–2001 (ha)
Okinawa	23.0	41.3
Miyako	1.6	6.5
Ishigaki	78.2	87.1
Iriomote	433.9	503.0
Kohama	3.4	5.6
Total	540.1	643.5

Source: ISME (2004)

According to ISME (2004), Iriomote Island has 503 ha of mangroves in 2001 or nearly 70% of the total area of mangroves in Japan. As shown in Table 18.3, the total mangrove area of these five islands was 540.1 ha in 1977 and 643.5 ha in 2001, an increase of 19%.

Mangroves of Japan are gradually increasing in area because most of the mangroves in Okinawa are well conserved. According to ManGlobal (2019), the total extent of mangroves in Okinawa is 788.5 ha. Mangrove distribution elsewhere is estimated to be ~90 ha. Hence, the total extent of mangroves in Japan is ~870 ha.

After World War II, Okinawa came under the control of the US Civil Administration of the Ryukyu Islands (USCAR). When Okinawa was returned to Japan in 1972, forests including mangroves managed by the Government of Ryukyu Islands were managed by the Forestry Agency of Japan as national forests. All forests including mangroves of Iriomote Island were designated as a National Park. In 2019, all areas on Iriomote Island including private land areas and some areas of Ishigaki Island were designated as Iriomote–Ishigaki National Park by the Ministry of the Environment. Iriomote Island was designated as a Natural World Heritage Site in July 2021 (UNESCO World Heritage Center 2021).

18.1.4 Highlights of Some Mangrove Species

Kandelia has long been regarded as a monotypic genus with *Kandelia candel* as the only species. Recent studies in chromosome number, molecular phylogeography, physiological adaptation, and leaf anatomy by Sheue et al. (2003) have revealed that there are two well-differentiated sets of geographical populations separated by the South China Sea. The two distinct species are *K. candel* and *K. obovata*. The population stretching from southern Japan to the Hainan Island in China is *K. obovata* while that in South and Southeast Asia is *K. candel*. In Okinawa, *K. obovata* is a pioneer species that shows natural regeneration (Khan and Kabir 2017). In most localities, it is monospecific forming closed canopy stands while in a few patches, *R. stylosa*, *B. gymnorhiza* and *E. agallocha* are also observed. Since Okinawan *Rhizophora* species is confused, we try to provide clear explanation in Box 3.1.

Box 3.1 Unraveling the Okinawan *Rhizophora* Puzzle

There is much confusion regarding Okinawan *Rhizophora*. In Flora of Okinawa and the Southern Ryukyu Islands (Walker 1976), two species, *R. mucronata* and *R. stylosa*, were recorded. Hatusima (1975) considered *R. mucronata* as a synonym of *R. stylosa* without noting style length. However, Hatusima and Amano (1977) employed *R. mucronata* instead of *R. stylosa*. Walker (1976) described the style in *R. mucronata* as obscure or very short (at most 1.5 mm long) and stamens as sessile and the *R. stylosa* style as filiform (2–6 mm long) and stamens distinctly short and filamentous. However, in the Botany of Mangroves (Tomlinson 2016) describes the stigma in *R. mucronata* as sessile and leaf blade as broad and long (10 × 20 cm) and in *R. stylosa* the slender style (4–5/6 mm) and the leaf blade as narrow and short (7 × 12 cm).

Fortunately, more than 25 years ago, some Japanese mangrove scientists brought propagules of *R. mucronata* from Thailand and planted them at Funaura Bay mangrove forests on Iriomote Island. One of the planted trees grew about 6 m in height producing flowers and fruits. About 15 years ago, one of the islanders collected a *Rhizophora* with very long propagules from Iriomote Island and planted a tree at Urauchi River that grows almost 5 m tall bearing flowers and fruits. We collected leaves and flowers from the three *R. mucronata* trees as shown in Figs. 18.2 and 18.3.

(continued)

Fig. 18.2 Leaves and flowers of three *Rhizophora* trees on Iriomote Island

Fig. 18.3 Flower parts of three *Rhizophora* species on Iriomote Island. Styles of the *Rhizophora* trees from Thailand and of the unknown are obscure, but those native to Iriomote are filiform and 4–5 mm long

Box 3.1 (continued)

The morphological features of Okinawan *Rhizophora* are obviously those of *R. stylosa* and not *R. mucronata*. Occasionally, propagules of *R. mucronata* do drift to Okinawan coasts from nearby countries and grow naturally. Hybridization between the two species is a possibility.

(Written by S. Baba)

18.2 Mineral Nutrients in the Leaves of Two Mangrove Species

18.2.1 Introduction

Mangrove forests are located on tidal flats between the land and sea and thus are receiving inputs of mineral nutrients both from river and seawaters. Tree roots take up water containing mineral nutrients from the soils, and the minerals are transported to the leaves. These elements play essential roles in bioprocesses in the leaves, and the excess elements are stored in the leaves, which finally drop off as litter (Lambers and Oliveira 2019). Contents of mineral nutrients in the leaves vary among plant species, also reflecting the nutrient condition where the plants live. Information of mineral nutrients dynamics will contribute to the understanding of plant–environment relations.

Mangrove plants have adapted to saline environments (halophytes), and thus they possess tolerance against high salinity, consisting primarily of sodium, magnesium, calcium, chloride, and sulfate. Although there are many studies on the effects of sodium on mangrove plant growth (e.g., Wang et al. 2011), the number of studies focusing on other mineral nutrients in mangrove plants is limited.

This section provides a case study that measured the content of mineral nutrients in mangrove rivers and in the leaves of two mangrove species, *B. gymnorhiza* and *R. stylosa*, on southwest islands of Japan.

18.2.2 Materials and Methods

Surveys were conducted at seven mangrove forests on Ishigaki and Iriomote Islands in Okinawa Prefecture, Japan. For each site, mature leaves were sampled from three individuals for each species of *B. gymnorhiza* and *R. stylosa*. We selected the sample trees of the two species growing side by side. The sampled leaves were dried at 80 °C until their weight became constant and were ground into fine powder. The powder samples were added to a mixture of 60% HNO_3 and 30% H_2O_2 (1:1) and digested by a microwave pressure digestion system (Speedwave MWS-3^+, Analytikjena, Jena, Germany). Mineral contents of the resultant solution were measured by an ICP-AES analyzer (ICPE-9820, Shimazu, Japan). At each site, 50 mL of river water was sampled beside the leaf-sampled trees, and the water was filtered with 0.45 μm mesh filter (DISMIC 25CS, ADVANTEC, Tokyo, Japan) immediately after the sampling and stored in 5 °C until the measurement of mineral contents in the laboratory. The contents of minerals in the river water were measured by the ICP-AES analyzer.

18.2.3 Results and Discussion

18.2.3.1 Content of Mineral Nutrients in Mangrove Rivers

Figure 18.4 indicates the relation between contents of sodium and other minerals in mangrove river waters on southwest islands in Japan. Among the elements, boron, calcium, potassium, magnesium, and sulfur contents showed a clear positive relationship with the sodium content, indicating that these elements originated from seawater. Therefore, the contents of these elements in mangrove river water can be fluctuated with tidal events. As for silica, there was a negative relationship with the sodium content leading to an interpretation that the content of this element can reflect the extent of inland water input. The remaining elements (ferrous, manganese, and phosphorus) did not show any clear relationship with the sodium content. The contents of these elements in mangrove river water were less than 0.5 mg L^{-1} (microelements) and can be site-specific features.

18.2.3.2 Mineral Elements in Mangrove Leaves and River Water

Figure 18.5 indicates the bioconcentration factor, which was obtained by dividing mineral contents of leaves by those of river water, for the nine minerals of two

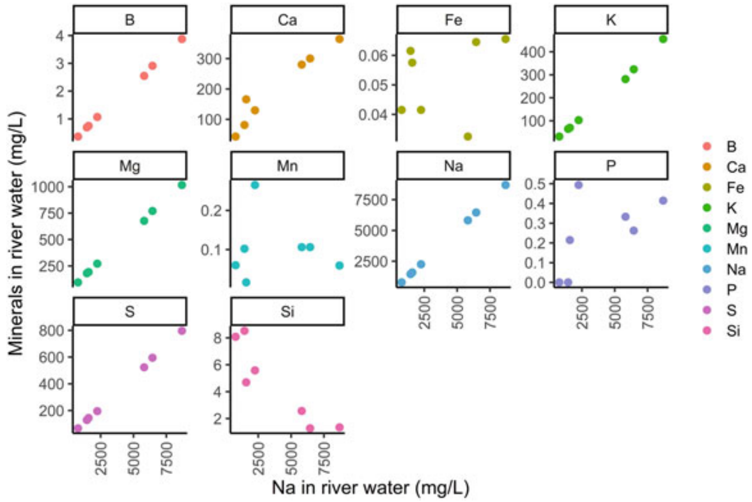

Fig. 18.4 Relationship between mineral nutrients and sodium contents in mangrove river waters in southeast islands, Japan

mangrove species. To solve the effects of seawater on the mineral contents in river water, each element was standardized by the sodium content prior to the calculation of bioconcentration factor. The leaf sodium content did not significantly differ between the two species (1.26 ± 0.34 wt% for *B. gymnorhiza* and 1.14 ± 0.52 wt % for *R. stylosa*, respectively). Among the nine elements, the bioconcentration factor of the eight elements other than silica (B, Ca, Fe, K, Mg, Mn, P, and S) was higher than 1. This indicates that the eight elements accumulated in leaves of the two mangrove species, while silica did not. There were interspecific differences in the accumulation pattern of the elements between the two mangrove species. *B. gymnorhiza* showed higher leaf content of sulfur than *R. stylosa*. It has been well known that wetland soils include high content of reduced form of sulfur, such as HS^- and S^{2-} (Mitch and Gosselink 2007). Plants can control absorption of SO_4^{2-} physically, but they cannot control uptakes of HS^- and S^{2-}. Although sulfur is essential for protein synthesis in the plant body, the required content is not so high (about 0.1%), and thus plants need to eliminate the excess sulfur, such as sequestration into vacuoles, and shed as leaf litter. Some aquatic plants synthesize dimethylsulfoniopropionate (DMSP) in their body, which is a volatile and unstable compound, and DMSP will be decomposed into dimethyl sulfide (DMS) and methanediol emitting to the air (Steudler and Peterson 1984). Our results indicate that the two mangrove species may differ in the manner or ability of sulfur elimination. Among the other elements, *R. stylosa* showed higher leaf contents of calcium, potassium, magnesium, manganese, and phosphorus than *B. gymnorhiza*. Calcium, potassium, and magnesium can be characterized by seawater (Fig. 18.5). *R. stylosa* has a habit to distribute on seaward areas (Tomlinson 2016), and thus this species

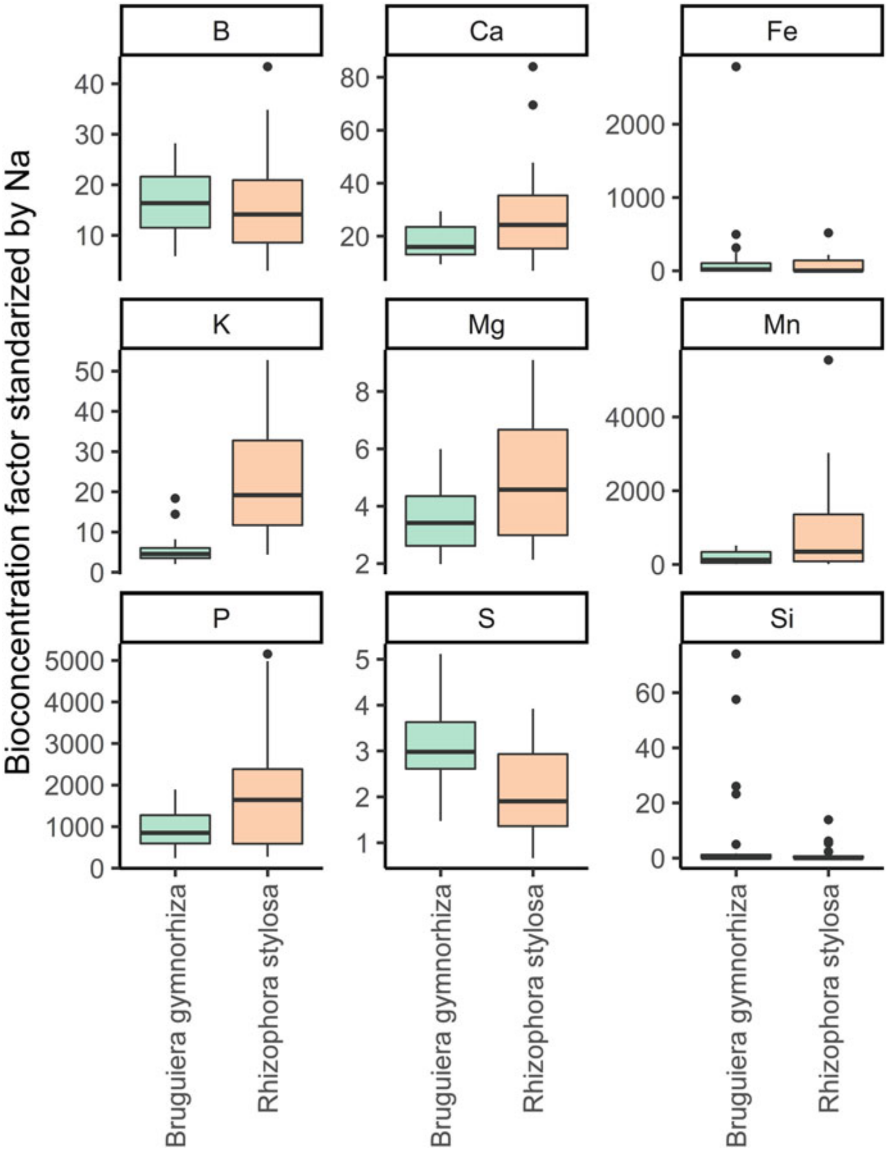

Fig. 18.5 Bioconcentration factor standardized by sodium content in the leaves of mangrove plants, *Bruguiera gymnorhiza* and *Rhizophora stylosa*

may have developed properties to accumulate these seawater-derived elements in its leaves. Here, we analyzed the data standardized by the sodium content, and the observation was the snapshot data for mature leaves. Measurement on mineral contents based on leaf ages will give us further understanding on species-specific mineral uptake and elimination dynamics.

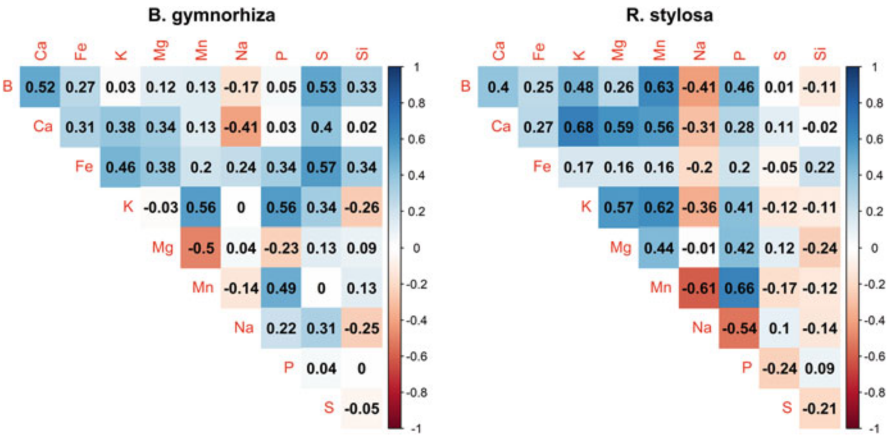

Fig. 18.6 Relationship among minerals in mangrove leaves of *Bruguiera gymnorhiza* and *Rhizophora stylosa*. The numbers and colors in the matrix indicate correlation coefficients between the elements

18.2.3.3 Relations Between Contents of Minerals in Mangrove Leaves

Figure 18.6 indicates the correlation among mineral contents in the leaves of two mangrove species. There were positive relations between phosphorus and manganese contents and between potassium and manganese contents in both mangrove species. In other terrestrial plants, it has been suggested that leaf manganese content can be used as a proxy for the root carboxylate-releasing processes under low phosphorus condition, which is a well-known strategy for efficient phosphorus acquisition (Pang et al. 2018; Lambers et al. 2015). This occurs because the carboxylates mobilize not only soil inorganic and organic phosphorus but also a range of mineral nutrients, including manganese. Mangrove soils are basically low in phosphorus (Alongi et al. 1992), and roots of mangrove plants are known to exude organic acids (e.g., Wang et al. 2014; Liu et al. 2017). Therefore, the observed positive relation between phosphorus and manganese contents in mangrove leaves in this study also may reflect the root organic acid exudation.

Among the minerals derived from seawater (B, Ca, K, Mg, and S), co-accumulation patterns were observed, but the combinations of the elements differ between the two mangrove species (Fig. 18.6). In the leaves of *B. gymnorhiza*, a positive relationship was observed among the contents of boron, calcium, and sulfur. In contrast, a positive relationship was observed among calcium, potassium, and magnesium in the leaves of *R. stylosa*.

Other features observed in *B. gymnorhiza* were the positive relationship between ferrous and sulfur and the negative relationship between magnesium and manganese. In contrast, *R. stylosa* showed positive relationships between manganese and boron and between manganese and calcium, and negative relationships between manganese and sodium and between sodium and phosphorus. These observations indicate that the two mangrove species differ in their habitat mineral characteristics and/or uptake, transport, and accumulation processes of mineral nutrients.

18.2.4 Conclusions

Our observations suggest that the content of mineral nutrients in mangrove river water can partly be explained by the effect of seawater (B, Ca, K, Mg, Na, and S) and inland water (Si). In addition, microelements (<0.5 mg L^{-1}) reflect the site-specific features, such as ferrous, manganese, and phosphorus in this study. Receiving the input from mangrove river water, leaves of mangrove plants function as a concentration system for the mineral nutrients, and the extent of the concentration varies among elements and plant species. Measurements on the processes supporting the observed pattern of the leaf mineral contents will contribute to the further understanding of both mangrove plant physiology and elemental dynamics in mangrove forests.

18.3 Decapod Crustaceans Inhabiting Mangrove Ecosystems

18.3.1 Introduction

The order Decapoda is one of the major crustacean taxon which includes crabs, shrimps, and hermit crabs. They have been adapted to diverse environments from the deep sea to shallow waters, brackish to freshwater waters and even terrestrial environments. Mangrove environments are also known to host a large variety of decapod crustaceans. The Japanese archipelago spans over 3500 km along the eastern coast of the Eurasian continent from subtropical to subarctic climate zones. The relatively small islands scattered over 1000 km southwest of the Japanese archipelago are distributed by natural mangroves (see Spalding et al. 2010). Due to insular environments with limited land area, zonations of mangroves in Japan are sometimes not as clear as those seen in continents or very large islands; habitat segregations of decapod crustaceans are often not so clear.

A total of 98 species of decapod crustaceans have been reported from mangrove environments in Japan, and unrecorded species and even undescribed species have been regularly discovered. Although the picture of decapod fauna of mangrove environments in Japan is still not uncovered, this section aims to provide an overview on their faunal, distributional, and ecological features.

Table 18.4 Decapod crustacean species inhabiting mangrove environments in Japan

Suborder	Infraorder	Subsection	Family	No. of species	Percentage
Dendrobranchiata			Penaeidae	4	4.0
Pleocyemata	Caridea		Alpheidae	1	1.0
			Atyidae	1	1.0
			Palaemonidae	4	4.0
			Hippolytidae	1	1.0
	Axiidea		Callianassidae	1	1.0
	Gebiidea		Laomedidae	1	1.0
			Thalassinidae	1	1.0
			Upogebiidae	2	2.0
	Anomura		Coenobitidae	1	1.0
			Diogenidae	5	5.1
	Brachyura	Heterotremata	Oziidae	2	2.0
			Leucosiidae	2	2.0
			Hymenosomatidae	2	2.0
			Portunidae	5	5.1
			Pilumnidae	2	2.0
		Thoracotremata	Gecarcinidae	2	2.0
			Grapsidae	5	5.1
			Sesarmidae	25	25.3
			Varunidae	6	6.1
			Camptandriidae	3	3.0
			Dotillidae	3	3.0
			Macrophthalmidae	11	11.1
			Mictyridae	1	1.0
			Ocypodidae	8	8.1

18.3.2 Faunal Components and Their Habitat Use

Faunal studies of decapod crustaceans in the Japanese mangrove environments started in the 1930s by Sadayoshi Miyake. Later, Yukio Nakasone and Shigemitsu Shokita conducted faunal and ecological studies in the Nansei Islands and accumulated further information. Despite these pioneering works, the discovery of unrecorded species and even species new to the science still continues till the present day (e.g., Nagai et al. 2011; Japanese Association of Benthology 2012; Maenosono and Saeki 2016).

Among the adults of decapod crustaceans from mangrove environments in Japan, Brachyura (crabs) is the most species-rich group (77.8%), followed by Caridea (shrimps, 7.0%), Anomura (hermit crabs, 6.1%), Dendrobranchiata (shrimps) and Gebiidea (mud shrimps) (both 4.0%), and Axiidea (ghost shrimps, 1.0%) (Table 18.4). However, this number is clearly underestimated as some taxonomically

Fig. 18.7 *Thalassina anomala*

difficult groups, for example, Alpheidae (snapping shrimps), are not properly counted.

The Japanese mangrove brachyurans comprises 14 families, of which Sesarmidae is the most species-rich family. Sesarmid crabs usually hide among roots of mangroves, under rocks or burrows of theirs and other organisms including arboreal habitats. They are generally more active in nighttime (Box 3.2). Some members are known as herbivores (e.g., *Neosarmatium smithi*; Matsutani et al. 2013). Another major member of the brachyurans is Macrophthalmidae (sentinel crabs) and Ocypodidae (fiddler crabs) belonging to superfamily Ocypodoidea. These ocypodoid crabs are detritivores, usually living in their burrows, and more active during daytime. Although the number of sentinel and fiddler crabs inhabiting mangrove environments in Japan is limited, more members are living on exposed tidal flats. As in other countries, mud lobsters contribute to make characteristic views with their mounds of their burrows, which also provide habitats for other creatures. Only one species of mud lobster, *Thalassina anomala* (Fig. 18.7), has been recorded from Japan.

Commercial mangrove crustaceans are limited in present-day Japan. They include the mud crabs (*Scylla serrata*, *S. olivacea*, and *S. paramamosain*), which are consumed by local people, but their landings and outputs for commercial fisheries are limited. The annual output of “swimming crabs” (*Scylla* spp. and blue swimming crab, *Portunus pelagicus*) during fiscal year 2019 in Okinawa Prefecture, where most of the mangroves occur, was only 18 million Jpn yen (Okinawa General Bureau 2021). The majority of these crabs is *P. pelagicus* (e.g., Sata et al. 1993).

Tiger prawns, *Penaeus monodon*, are also distributed in Japan, but its population size appears to be very small.

Mangrove environments are also important for temporal users. For example, 30 species of freshwater shrimps (Atyidae and Palaemonidae) have been reported from freshwater rivers in Japan with mangrove forests at their estuaries (Hayashi 2011; Suzuki and Naruse 2011). These shrimps have an amphidromous life history, and their larvae may be using mangrove estuaries as nursery grounds.

18.3.3 Distributional Features

Among decapod crustaceans in the Japanese mangrove environments, about 64.7% (64 species) of the species belong to Thoracotremata (e.g., Grapsoidea and Ocypodoidea; Table 18.4). About 71.9% of the thoracotrematan species are widely distributed in the Indo-West Pacific or Pacific regions. Recent studies have, however, shown that some species previously thought to be widely distributed turned out to have much narrower distributional ranges. For example, soldier crabs of the genus *Mictyris* in Japan had been identified as *M. brevidactylus*, but Davie et al. (2010) found that Japanese *Mictyris* was indeed a new species; the species is described as Japan endemic *M. guinotae*. Table 18.5 indicates mangrove-related crab species that are endemic to the Nansei Islands. Although all thoracotrematan species are thought to produce a large number of small eggs, suggesting the presence of planktonic larval phase in their life history, it is unclear why some of them are endemic to relatively small areas (e.g., East Asia or Ryukyu Islands) (Box 3.3). Another example of division of widely distributed species is the tree-spider crab, *Parasesarma leptosoma*, which was believed to be widely distributed from South and East Africa to Fiji, but a recent detailed study divided the species into nine species, with the Japanese species newly described as *P. gecko* (Li et al. 2018). Furthermore, Shahdadi et al. (2020) separated all *leptosoma*-like species from *Parasesarma* and transferred them to the genus *Leptarma*. As indicated by these examples, there is still room to improve their systematics, which may provide a different picture of their distributional features.

Box 3.2 Tree-Climbing Decapod Crustaceans

If you go to the mangrove forests at night, you may notice many nocturnal crustaceans are walking around and even climbing trees. Crabs of the family Sesarmidae (e.g., *Parasesarma bidens*, *P. semperi*, and *Episesarma lafondii*) and Grapsidae (e.g., *Metopograpsus latifrons*) (Fig. 18.8a) are commonly observed on trees at night, while sesarmid *Leptarma gecko* (Fig. 18.8b) are often seen even during daytime. Interestingly, a “tree climber hippolytid shrimp,” *Merguia oligodon* (Fig. 18.8c), is sometimes seen between buttress

(continued)

Table 18.5 Nansei endemic decapod crustaceans inhabiting mangrove environments

Species	Family	Adult habitat	References
Chiromantes ryukyuana	Sesarmidae	Near mangrove back forest	Naruse and Ng (2008)
Helice epicure	Varunidae	Near mangrove back forest	Ng et al. (2018)
Paramoguai pyriforme	Camptandriidae	Pebbly muddy substratum in riverbeds	Naruse (2005)
Apograpsus paantu	Macrophthalmidae	Pebbly muddy substratum in riverbeds	Naruse and Kishino (2006)
Scopimera ryukyuensis	Dotillidae	Sand flat	Wong et al. (2010)
Tmethypocoelis choreutes	Dotillidae	Sand flat	Davie and Kosuge (1995)
Mictyris guinotae	Mictyridae	Sand flat	Davie et al. (2010)

Fig. 18.8 Tree-climbing decapod crustaceans: (**a**) *Metopograpsus latifrons* (Grapsidae); (**b**) *Leptarma gecko* (Sesarmidae); and (**c**) *Merguia oligodon* (Hippolytidae)

Fig. 18.9 Brooding habits of "ovovivipary" in *Neorhynchoplax yaeyamaensis* (Hymenosomatidae): (**a**) dorsal view; (**b**) ventral view; eyed eggs of "ovoviviparous" crab retained in its body can be seen through its semitransparent cephalothorax and pleon (**a**, **b**). (**c**) *Leptarma gecko* (Sesarmidae) with normal brooding habits, ventral view showing eggs held externally. *ce* cephalothorax, *e* eggs, *pl* pleopod, *pv* ventral side of pleon

Box 3.2 (continued)

roots of *Bruguiera gymnorhiza* about 20–30 cm above the ground at low tide. Together with the Atlantic *M. rhizophorae*, *Merguia* species are only 2 out of more than 3400 caridean species (Holthuis 1958; Abele 1970; De Grave and Fransen 2011) that climb out of the water. Some *Macrobrachium* species have been observed walking on a road near streams, but unlike *Merguia* shrimps, they usually follow flooded water during or after heavy rain. It is still not understood why only *Merguia* species stay out of the water for a certain amount of time.

Table 18.6 Annual numbers of tourists to Ishigaki Island and Iriomote Island in comparison to population of islands 2007–2019

	2007	2008	2011	2013	2015	2017	2019
Tourists in Ishigaki	963,277	728,559	656,768	937,024	1,106,320	1,376,658	1,471,691
Population of Ishigaki	48,180	48,635	48,755	48,808	49,160	49,380	49,801
Ratio (a/b)	20	15	13	19	23	28	30
Tourists in Iriomote	405,646	340,440	254,611	346,401	387,952	315,294	290,313
Population of Iriomote	2325	2284	2267	2304	2398	2417	2457
Ratio (a/b)	174	149	112	150	162	130	118

Box 3.3 "Ovoviviparous" Crabs

Females of most brachyuran crab species hold their eggs externally, namely, fertilized eggs are attached onto their pleopods that develop from the thorax side of the pleon (Fig. 18.9c). Some groups of the family Hymenosomatidae, however, practice "ovovivipary"-like brooding habit. For example, mangrove-dwelling false spider crab, *Neorhynchoplax yaeyamaensis*, brood their eggs in a cavity formed within pleon to cephalothorax (Fig. 18.9a, b; Naruse et al. 2005). Although it has not been known how and where the larvae of *N. yaeyamaensis* grow, the species has so far been known only from Iriomote and Ishigaki of the Nansei Islands. *Neorhynchoplax* is currently known by 33 species mainly from tropical to subtropical Indo-Pacific regions (e.g., Ng and Chuang 1996; Hsueh 2018); many of them are also known to adopt "ovovivipary" (e.g., Ng and Chuang 1996; Ng 2015) and reported from relatively small geographical area.

18.4 Tourism and Beach Cleaning on Iriomote Island

18.4.1 Number of Tourists Visiting

Mangroves are one of the attractive tourist destinations in Okinawa Prefecture, especially in Iriomote Island. The annual number of tourists visiting Ishigaki and Iriomote Islands is much higher than the population of these islands. Table 18.6 shows the number of tourists visiting Ishigaki and Iriomote Islands from 2007 to 2019. On Iriomote Island, the total number of tourists that visited the island in 2019 was 118 times that of the resident population (Ishigaki City 2009, 2021; Okinawa Prefecture Government 2021; Taketomi Town 2021) (Table 18.6).

Iriomote Island is the second largest island of Okinawa Prefecture with a land area of 289.62 km^2 (Geospatial Information Authority of Japan (GIS) 2021). There is no

Fig. 18.10 The giant *Heritiera littoralis* tree beside Nakama River on Iriomote Island

airport on the island. The only way to get to the island is by a ferry from Ishigaki Island, which is about 30 km away. Most tourists visit Iriomote Island as a day trip and return to Ishigaki Island. Local inhabitants of Iriomote Island conserve the nature well and uphold their traditional cultures. On the island are many endemic and endangered mammals, birds, and insects. The Iriomote wild cat (*Prionailurus bengalensis iriomotensis*) is an endemic and critically endangered wild cat. The beautiful crested serpent eagle (*Spilornis cheela*) is an attraction. Nature in the form of undisturbed hill forests, rivers, mangroves, corals, and the beautiful sea are very attractive for the tourists. Popular events for the tourists include mangrove river cruises by tour-boats, canoeing through mangrove rivers, hiking and trekking in the mangroves and inland forests, bird-watching, snorkeling, scuba diving, recreational fishing, etc.

Tourists taking a boat cruise on the Nakama River on Iriomote Island will get a chance to trek the forest to see a giant *H. littoralis* tree. Measuring 23 m tall, 3.1 m in buttress height, and 345 cm in trunk girth, this magnificent tree is estimated to be 350 years old. Discovered in 1982, the tree is currently managed by the Okinawa Forest Management Office (Fig. 18.10). In 2000, the tree was designated as one of

Table 18.7 Breakdown of drifted garbage collected in Iriomote in 2020

Plastic garbage			Other garbage		
Material	Amount of collected garbage	Percentage	Material	Amount of collected garbage	Percentage
Styrofoams	511.0	34.39	Glassware	34.6	2.33
Other plastics	314.0	21.13	Metals	19.0	1.28
PET bottles	267.0	17.97	Light bulbs	10.6	0.71
Plastic buoys	237.2	15.97	Cans	9.3	0.63
Ship/fishing gear	39.3	4.66	Dangerous cans	7.5	0.50
			Rubber product	3.0	0.20
			Electrical appliances	1.5	0.10
			Cloth products	1.0	0.07
			Paper products	0.4	0.03
			Batteries	0.3	0.02
Plastic total	1368.5	94.12	Other garbage total	87.2	5.87

The amount of collected garbage is based on the number of 45-l polybags. Source: Iriomote Island Eco-Tourism Association and International Society for Mangrove Ecosystems (2021)

the "100 Forest Giants" by the Forestry Agency of Japan (Ministry of Agriculture, Forestry and Fisheries (MAFF) 2019).

18.4.2 Beach Cleaning Activities on Iriomote Island

Drifted garbage gets washed up not only on beaches but also gets entangled in the mangrove forests. A local NGO, the Iriomote Island Eco-Tourism Association, has been organizing monthly beach cleanup activities in collaboration with local residents, schools, and other organizations for more than 10 years. In 2019, a total of 464 people participated in the activity and collected 1350 bags filled of drifted garbage. A collection of 1350 bags (45 l each) of garbage would mean that more than 60,000 l of garbage were collected during that beach cleanup in 2019.

According to the association, over 90% of the drifted garbage collected from the beaches and mangrove forests were plastic products such as styrene foams, buoys, polyethylene terephthalate (PET) bottles, fishing gears/ropes, etc. (Iriomote Island Eco-Tourism Association and International Society for Mangrove Ecosystems 2021) (Table 18.7, Figs. 18.11 and 18.12). There is no facility on Iriomote Island to treat

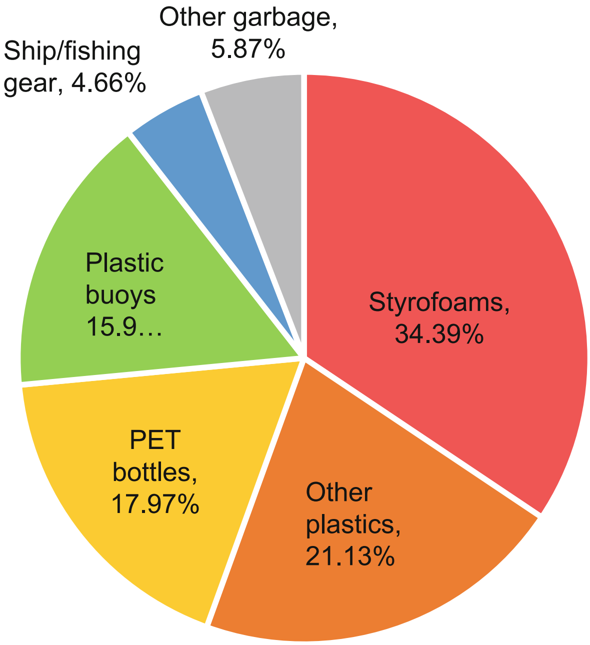

Fig. 18.11 Breakdown of collected garbage on Iriomote Island in 2020

Fig. 18.12 Drifted garbage on a beach of Iriomote Island

industrial wastes; therefore, they need to be shipped to neighboring Ishigaki Island at about US$1000 of shipping cost per trip (Baba et al. 2011; Iriomote Island Eco-Tourism Association 2012).

The drifted garbage that was washed up on the shore of Iriomote Island was mostly from other countries. To find out where the garbage comes from, the association started to read the barcodes of the drifted PET bottles since 2003. Results of the survey showed that most of the PET bottles originate from East Asian countries such as China, Taiwan, South Korea, and Japan and from Southeast Asia such as Vietnam, Malaysia, Indonesia, the Philippines, Thailand, and Singapore. Some even came from as far as the Middle East, Europe, Africa, and Americas (Iriomote Island Eco-Tourism Association 2012). It is likely that some might be thrown away from ships.

In recent years, Styrofoams are separated from other garbage and shipped to Hatomajima Island, about 5.5 km north of Iriomote Island, to extract styrene oil using a petrochemical machine that can be used as fuel locally.

However, the garbage problem cannot be solved just by collecting garbage. Taking advantage of the fact that more than 300,000 tourists visit the island each year, the association plans to organize beach cleanup events for tourists so that they can be more aware of the need to protect the environment and to keep the beaches and other coastal areas clean. Since most of the drifted garbage is from many countries overseas, this problem cannot be solved without international cooperation.

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Chapter 19
Mangroves of Ecuador

Fausto V. López Rodríguez

Abstract Between the 1970s and 1990s, Ecuador lost 27.6% of its mangrove forest, mainly due to the shrimp industry and urban expansion. In response to these threats to mangroves, Ecuador developed several strategies, including the creation of protected areas and the Sustainable Use and Custody Agreements for the Mangrove Ecosystem (AUSCEM), also called "mangrove concessions." More than 10,000 families on the Ecuadorian coast rely on mangroves as their main livelihood, especially the extraction of black shell (*Anadara tuberculosa*) and red crab (*Ucides occidentalis*). This strategy of conservation and sustainable use of the mangrove is so important that it protects 42.86% of the mangrove, almost the same extension as the protected areas (45.15%). The first mangrove concessions were signed in 2000 in the province of El Oro, located in southern Ecuador. This chapter includes an analysis of the management effectiveness of 20 AUSCEMs in this province.

Keywords Mangrove conservation · Mangrove biodiversity · Mangrove concessions · Mangrove threats · Management Effectiveness

19.1 Introduction

Ecuador has a population of 16,625,775 inhabitants and an extension of 256,670 km^2; it is bordered to the north by Colombia, to the south and east by Peru and to the west by the Pacific Ocean. With 64.85 inhabitants/km^2, it is the most densely populated country in South America (SENPLADES 2017) (Fig. 19.1).

The Coast has a length of approximately 1200 km (excluding the Galapagos Islands) (SENPLADES 2017). This region is highly diverse and productive with a great diversity of ecosystems. According to the Salm and Clark (1989) classification, 21 of the 27 globally recognized marine and coastal ecosystems are found in Ecuador: 10 of the 14 marine ecosystems and 11 of the 13 coastal ecosystems.

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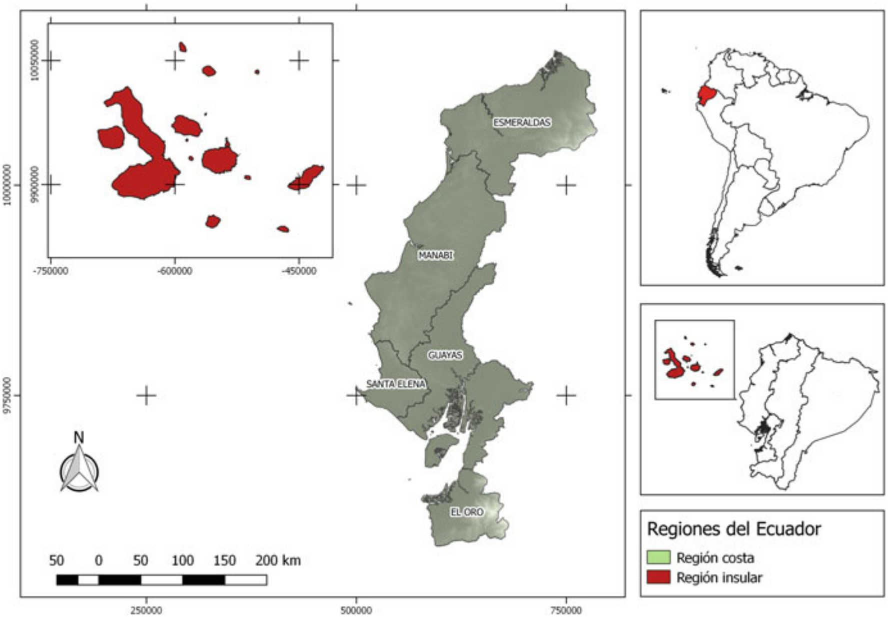

Fig. 19.1 Coastal and insular region of Ecuador. 39% of Ecuador's population lives on the coast

19.2 Physical Attributes and Characteristics

Mangroves are swampy forests that develop at the point where a river slope meets an arm of the sea. Relatively quiet places such as estuaries, bays, lagoons, canals, and inlets are home to these magnificent trees that give their environment their name. One of the main characteristics of mangroves is their tolerance to waters with a high concentration of saline water. However, depending on the type of mangrove, they have different salinity concentrations, some of them with very salty waters such as fringe mangroves and others with less salty waters such as riparian or basin mangroves. Another important characteristic is the type of soil in which they grow, since the presence of mangroves predominates in soft soils such as sand, silt, or clay, but never in rocky soils.

In these ecosystems, water circulates very slowly, which causes sediments from the continent to settle to the bottom of the sea (Astudillo et al. 2014). The adverse characteristics of the soil where the mangrove develops, such as high salinity and oxygen deficiency, are compensated through extraordinary forms and adaptation mechanisms, such as the "aerial" roots that help the plant to absorb oxygen, as in the case of the red mangrove (*Rhizophora mangle*), which start from the trunk or lateral branches and fall to the ground. This species is capable of filtering and dosing salt water through fine membranes located in its roots. In some species, the roots contain high levels of waxy suberin to mitigate the level of salt entering the cells. Other species, such as the white mangrove (*Laguncularia racemosa*), is capable of secreting the salts it has in excess (Astudillo et al. 2014).

In Ecuador, mangroves are located along the coast predominately in the provinces of Esmeraldas, Manabí, Guayas, El Oro and in the Galapagos Islands. Large mangrove formations are found in estuaries of the Mataje-Santiago-Cayapas, Muisne, Cojimíes, Chone, Guayas, and Jubones-Santa Rosa-Arenillas rivers. The most extensive area of mangroves is found in the estuary of the Guayas River and the Gulf of Guayaquil (83% of Ecuador's mangroves are located here). However, due to better climatic conditions, the Santiago-Cayapas-Mataje estuary zone (Esmeraldas Province) is the one with the best development of mangroves (MAE-Ministerio del Ambiente del Ecuador et al. 2014).

The mangroves in Ecuador, according to their location, are divided into three types (Cintrón et al. 1985):

Fringe Forest They are the closest to the sea and are subject to daily flooding (more than 700 times per year). The province of Guayas has a large extension of this mangrove forest.

Riverine Forest It is found on the margins of the rivers. They tend to be taller than the fringe mangrove because they are exposed to fresher water. The vegetation is often dominated by *Rhizophora* spp.

Basin Mangrove These mangroves are the furthest from the sea, located near the salt flat areas. The best adapted trees and shrubs in these areas are *Avicennia germinans* and *Conocarpus erectus*. The largest areas with this type of forest are found in the province of Esmeraldas.

According to the Classification of the Ecosystems of Continental Ecuador, the mangroves of Ecuador are divided in two groups: Equatorial Chocoan mangrove for the northern zone and the Jama-Zapotillo mangrove for the central-southern zone. There are 22,961.07 ha in the Equatorial Chocoan Mangrove and 134,133.21 ha in the Jama-Zapotillo Mangrove which has its highest ecosystem representation in the province of Guayas (67.68%), followed by the province of El Oro (16.65%). The remaining area of this ecosystem is located in the province of Esmeraldas with a percentage of 14.49%. On the other hand, 97% of the Chocoan mangrove forest is located in the province of Esmeraldas. The province of Manabí has only 1.18% of mangroves, but it has presence of both Manglares Chocoan and Jama-Zapotillo (Ministerio del Ambiente del Ecuador 2013).

The Equatorial Chocoan Mangrove Dense forests with closed canopy reaching 20 to 30 m high (65 to 98 ft). In Ecuador, the mangroves found in the Cayapas Mataje Mangrove Ecological Reserve, in the province of Esmeraldas, are the most structurally developed and are considered the tallest in the world. The tallest mangroves in the world have been recorded in Majagual (Esmeraldas), with trees up to 50 m high and with a diameter of more than 1 m. There are three co-dominant mangrove species: *Rhizophora mangle, R. racemosa,* and *R. x harrisonii.*

The Jama-Zapotillo Mangrove These mangrove forests are less developed in relation to The Equatorial Chocoan Mangrove. They develop at the interface from the mainland to the open sea and have a closed canopy that ranges from 10 to 12 m. The plant communities are distributed according to their specificity; toward the outside, there is *Rhizophora* spp. (red mangrove), followed by *Avicennia germinans*, then *Laguncularia racemosa* and finally *Conocarpus erectus*. This order depends very much on the degree of tolerance to salinity of each species (Ministerio del Ambiente del Ecuador 2013).

19.3 Floral Biodiversity

Cornejo (2014) in the publication *Plantas de los manglares de la costa del Pacífico de América del Sur* (Colombia, Ecuador, Peru) reports 49 families, 135 genera, and 222 species of vascular plants in the mangroves of the Pacific coast of Colombia, Ecuador, and Peru of which 179 species are present in Ecuador. Cornejo (2019) classifies the species as follows: major mangroves (5), minor mangroves (2), and facultative mangroves (6). The remaining species, which had previously been considered as "associated flora" is now classified as "other floristic elements."

Table 19.1 categorizes the mangroves of the región as major, minor, and facultative according to the types of morphological and physiological adaptations, in combination with the habitat they occupy and the role they play (Cornejo 2014). The major mangroves or true mangroves are those that have the facility to colonize and are dominant in the outermost fringe disposed toward the sea. The minor mangroves are those that colonize in the posterior portion of the mangrove. The facultative

Table 19.1 Types of mangroves in Ecuador

Families	Scientific name	Mangrove type
Rhizophoraceae	*Rhizophora mangle*	Major
Rhizophoraceae	*Rhizophora racemosa*	Major
Rhizophoraceae	*Rhizophora x harrisonii*	Major
Acanthaceae	*Avicennia germinans*	Major
Combretaceae	*Laguncularia racemosa* var. *racemosa*	Major
Combretaceae	*Laguncularia racemosa* var. *glabriflora*	Major
Tetrameristaceae	*Pelliciera rhizophorae*	Minor
Bignoniaceae	*Tabebuia palustris*	Minor
Fabaceae	*Mora oleifera*	Facultative
Fabaceae	*Pterocarpus officinalis*	Facultative
Combretaceae	*Conocarpus erectus*	Facultative
Malvaceae	*Talipariti tiliaceum* var. *pernambucence*	Facultative
Bignoniaceae	*Amphitecna latifolia*	Facultative
Annonaceae	*Annona glabra*	Facultative

Source: Cornejo (2014)

mangroves are proposed by Cornejo (2014) as a new category that encompasses *species links*, connecting the mangroves with freshwater, inland ecosystems. It is important to note that, although the mangrove plant species are of "least concern," the mangrove ecosystem in Ecuador is considered fragile and, therefore, all of its species should be considered threatened (Cornejo 2014).

19.4 Faunal Biodiversity

Mangrove fauna comprises dozens of species of birds, mammals, reptiles, fish, crustaceans, mollusks, insects, and arachnids that seek mangroves mainly as refuge, feeding, and/or breeding areas. Ecuadorian mangroves are home to 52 species of birds, 15 species of reptiles, 19 species of mammals, approximately 100 species of fish, 20 species of crustaceans, and 70 species of mollusks (MAE and FAO 2014). Ecuador's mangrove fauna also includes a tiny new species of mite (*Hattena rhizophorae*), a visitor of red mangrove flowers, which has been discovered in the country's mangroves; its genus was unknown for the American continent (Faraji and Cornejo 2006; Cornejo 2014).

19.4.1 Birds

Bird diversity in mangroves is not as rich as in the tropical rain forests, but the species composition is totally different. It is characterized by a low number of species, but a high numbers per species. This is an opportunity for tourism, especially ornithological tourism since travelers can observe many species in a short time. It is estimated that in one trip to the mangroves of Ecuador, 50 species can be easily observed. Some birds species include: mangrove black hawk, *Buteogallus anthracinus*; white ibis, *Eudocimus albus*; roseate spoonbill, *Ajaia ajaja*; and several species of herons, including great egrets, *Ardea alba*; snowy egrets *E. thula*; little blue herons, *E. caerulea*; tricolored herons, *E. tricolor*; green-backed herons, *Butorides striatus*, as well as black-crowned *Nycticorax nycticorax* and yellow-crowned *Nyctanassa violacea* night herons (Carvajal and Álava 2007).

Although only 52 species of birds are reported for Ecuador's mangroves, new research conducted in the Jambelí Archipelago (El Oro Province) has recorded 118 species (35 migratory and 83 resident species) belonging to 44 families (Orihuela-Torres et al. 2018), a relatively high number given the high rates of mangrove deforestation that occurred between the 1970s and 1980s. Nine of the 83 resident species are endemic to the coasts of Ecuador and northwestern Peru (Tumbesian Region) and six are in the IUCN "threatened" category. The most abundant species in the archipelago are Magnificent Frigatebirds (*Fregata magnificens*) and Neotropical Cormorants (*Phalacrocorax brasilianus*). The archipelago is also a wintering and stopover site for boreal migratory species (Orihuela-

Torres et al. 2018). This diversity of birds led Birdlife International to include the Jambelí archipelago among the 107 Important Bird Areas (IBAs) in Ecuador (BirdLife International and Conservation International 2005).

19.4.2 Herpetofauna

There are 13 species of herpetofauna (1 amphibian and 12 reptiles), mainly turtles and snakes. The most abundant species are the iguana (*Iguana iguana*) and the boa (*Boa constrictor imperator*). Several of these species are endemic and have been listed as "threatened" (MECN-INB-GADPEO 2015). Two species of sea turtles, hawksbill (*Eretmochelys imbricata*) and green (*Chelonia mydas*), reside in the Jambelí Archipelago, but do not nest there. The green turtle is observed more frequently than the hawksbill species. Both turtle species are considered "threatened" by IUCN. Mangroves provide habitats for the critically endangered American crocodile (*Crocodylus acutus).*

19.4.3 Mammals

Mammals include the crab-eating raccoon (*Procyon cancrivorus)* and neotropical otter, (*Lontra longicaudis)*. Bottlenose dolphins (*Tursiops truncatus*) are also common marine mammals residing around the mangrove estuarine waters along the Ecuadorian coast (Gulf of Guayaquil) (Carvajal and Álava 2007). Another interesting species is the Sechura mountain dog (*Lycalopex sechurae*). It has been reported on beaches near mangroves in the provinces of El Oro, Guayas, and Manabí. In desert areas and dry forests it feeds on fruits, rodents, birds, reptiles, insects, and scorpions. While along coastal beaches, it feeds on crabs, carrion, seabirds, and eggs (Vallejo 2019).

19.4.4 Commercial Species

Many of the mangrove faunal species are commercially important for food. Among the most important are the red crab (*Ucides occidentalis*), crabs (*Callinectes arcuatus, C. toxotes*), shrimps (*Litopenaeus stylirostris, L. vannamei*), black shell or blood cockle (*Anadara tuberculosa*), mussels (*Mytella* guyanensis), oysters (*Crassostrea columbiensis*), clams (*Protothaca* sp., *Chione subrugosa*), and dozens of fish species such as mullet (*Mugil cephalus*), corvina (*Cynoscion albus*), snook (*Centropomus* spp.), snapper (*Lutjanus* sp.), etc. (MAE and FAO 2014).

19.5 Phytoplankton, Zooplankton, and Microbial Diversity

There are few studies on Phytoplankton and Zooplankton in the mangroves of Ecuador. An important investigation was carried out in the Cayapas Mataje Mangrove Ecological Reserve in the province of Esmeraldas-Ecuador (northern Ecuador) between April 2000 and December 2001. A total of 257 phytoplankton species were identified, of which 24 were reported for the first time in Ecuadorian waters. Grouped in 37 families, Naviculaceae, Chaetoceraceae, and Bacillariaceae were the most numerous, especially in the dry period. Zooplankton was represented by 22 taxonomic groups and 44 species, the most common being *Acartia lilljeborgi* in the rainy season and *Acartia tonsa* in the dry season. *Acartia tonsa* is also the most representative species in Cojimíes, an area located between the limits of the provinces of Manabí and Esmeraldas. In this study, 14 families of zooplankton were found being *Paracalanidae*, *Oithonidae,* and *Acartidiidae* the most representative among the copepods. Among the 17 genera identified, *Arcatia* sp., *Paracalanus* sp., *Oithona* sp., and the cladoceran *Evadne* sp. were the most abundant (Ramos-Centeno and Napa-España 2018). Gaibor et al. (2007) identified *Macrobrachium* larvae and larvae of *Litopenaeus* shrimp, which are of commercial importance and local consumption (18%), but also species of ecological value such as mysidaceae, caridea, anomura, fish larvae, chaetognata, among others (12%). The northern zone of the Cayapas Mataje Reserve is the most productive and has the highest planktonic density, which means clean waters and low presence of human activities (Prado et al. 2012).

In a study conducted in the coastal zone of the province of El Oro (which is part of the estuary of the Gulf of Guayaquil), a total of 324 species were identified, distributed in 11 classes: 100 Bacillariophyceae, 23 Chlorophyceae, 109 Coscinodiscophyceae, 1 Cryptophyceae, 10 Cyanophyceae, 3 Dictyochophyceae, 52 Dinophyceae, 4 Euglenophyceae, 15 Fragilaryophyceae, 1 Trebouxiophyceae, and 6 Zygnematophyceae. The most frequent and abundant species throughout the study area were *Nitzschia longissima*, *Pseudo-nitzschia delicatissima*, *Skeletonema costatum*, *Paralia sulcata,* and *Guinardia striata*. *Skeletonema costatum* is one of the most abundant in the estuary of the Gulf of Guayaquil and plays a very important role in the trophic chain of the inner estuary, mainly as a useful species in the feeding of fish and crustaceans (Prado-España et al. 2015).

19.6 Ecosystem Services

There is a growing recognition of the importance of mangroves to mankind for the many environmental services they provide, especially to coastal communities. Several studies have been conducted to determine the economic value of the mangrove ecosystem, which vary by country and even region. In Sri Lanka, the direct benefit of mangroves has been estimated to be $12,229 per-year per-hectare, while in Kenya, this value is $1092. In northern Haiti, the ecosystem services of the mangroves were estimated at between $10,000 and $35,000 per-year per-hectare. In Puerto Rico, the cost of one hectare affected by oil spills is $751,368 (Hamilton and Collins 2013).

In Ecuador in 2001, the Ministry of the Environment established a cost of $89,273 per hectare for the loss of environmental goods and services and the cost of restoration due to logging, harvesting, transformation or destruction of mangrove forests. In the period 2012–2020 there was an accumulated collection of $1,568,873 in 18 sanctions, according to the entity. This amount is too low considering the number of reports of mangrove logging caused by shrimp companies (Ministerio del Ambiente del Ecuador 2011).

Mangrove coastal ecosystems are extremely important to global carbon storage ("a regulating service") as they have the capacity to store more carbon than many tropical forests. One of the most important ecosystem services of the mangrove is the "supporting" service and is based on the abundant supply of organic matter, which is fundamental for the life cycle of a great biodiversity, including commercial fisheries. It is estimated that 80% of global fish catches are directly or indirectly linked with mangrove ecosystems (Ellison 2008). The high fauna diversity provides the important ecosystem services of "provisioning" that play a fundamental role in food security and the economic activity of local communities. This ecosystem service is related to fishing and the harvesting of black shell (*Anadara tuberculosa* and *A. similis*), and crustaceans (*Ucides occidentalis*, *Callinectes arcuatus*, *C. toxins)* and shrimp (*Litopenaeus stylirostris, L. vannamei*).

The diversity of avifauna is particularly important for the "cultural service" of recreation and tourism. In this aspect it is important to highlight the fact that several community associations are undertaking ecotourism programs thanks to the scenic beauty and diversity of birds present in this ecosystem. Mangrove birds have a special characteristic because, in addition to being abundant, they can be easily observed, whether resting, nesting or flying. Birds are a resource of great importance for ecotourism, an activity that is beginning to be developed by several community organizations that have Agreements of Sustainable Use and Custody of Mangroves.

Recognition of the importance of ecosystem services differs between the Galapagos Islands and mainland Ecuador. While in Galapagos the main ecosystem services are: carbon storage, support for small-scale fisheries, and mangrove-based tourism (Tanner et al. 2019), in the Gulf of Guayaquil the services most recognized by several community organizations are fishery, nursery, and climate regulation. These services also agree with the three top ecosystem services that stakeholders would like to maintain most through time (Darquea 2016) (Fig. 19.2).

Although tourism is not mentioned in this study as a benefit of the mangroves, several communities have begun to develop tourism as a complementary activity to shell and crab harvesting.

Galapagos has only 3690 ha of mangrove coverage (which represent less than 3% of total mangrove of Ecuador), but is very relevant because it provides very important ecosystem services. Galapagos mangroves store about 211 tons of carbon

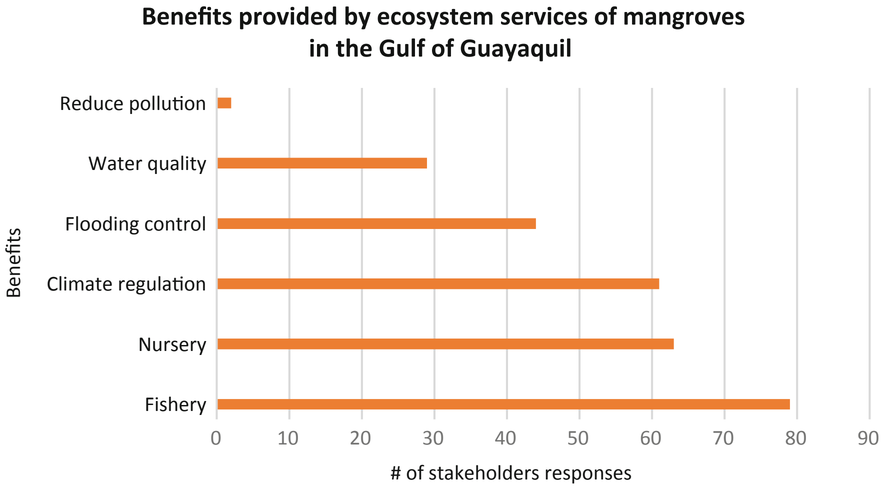

Fig. 19.2 Fishery, nursery, and climate regulation are the most important ecosystem services in the Gulf of Guayaquil according to the stakeholder perceptions. Source: Darquea (2016)

per hectare, which means more than 778,000 total tons of carbon, equivalent to 15% of Ecuador's annual carbon emissions in 2016. The carbon stored in Galapagos mangroves is worth between $10.8 million and $102 million, depending on the price per hectare of mangrove forest: $2940 or $27,852 per hectare (Tanner et al. 2019).

Fishery is also important. The Galapagos fin-fishery receives over $900,000 of net benefits each year from mangrove habitat. Snapper, mullets, and the lobster fishery are dependent on healthy mangroves as habitat and nursery areas (Tanner et al. 2019).

The contribution of mangroves to the tourism industry is very important. Tanner et al. (2019) estimate that 47% of all tourist sites in Galapagos are mangrove-based, and that the tourism sector receives over $62 million of revenue from visits to these each year. This is very important considering that about 80% of total employment in the Islands comes from the tourism industry.

However, the ecosystem services of Ecuador's inland mangroves are threatened by pollution of sediments and fauna, particularly mollusks, and crustaceans. High concentrations of heavy metals such as cadmium (Cd), lead (Pb), and mercury (Hg), total petroleum hydrocarbons (TPH), oils and fats, total coliforms, and *Escherichia coli* have been detected. Heavy metals and hydrocarbons are a consequence of industrial activities, especially mining, port activities, and the oil industry. The discharge of untreated sewage into the estuaries where the mangroves are located and the inadequate disposal of solid waste are the main sources of contamination by total coliforms and *Escherichia coli*. Agriculture and the shrimp industry also generate pollution from the use of fertilizers and pesticides (Pernia et al. 2019).

It has been demonstrated that there is accumulation of cadmium (Cd), lead (Pb), and mercury (Hg) in bivalves (*Anadara tuberculosa* and *Anadara similis),* oysters (*Crassostrea columbiensis*), mussels (*Mytella guyanensis* and *Mytella strigata*), and red crabs (*Ucides occidentalis*). Total and fecal coliforms were also detected in *Anadara tuberculosa*, *Anadara similis*, *Crassostrea columbiensis,* and *Mytella guyanensis*, particularly in the mangroves of the provinces of El Oro and Guayas (Pernia et al. 2019).

19.7 Regeneration of Mangrove/Silviculture

The shrimp industry has been identified as mainly responsible for mangrove loss in Ecuador. Between 1969 and 2006, the area occupied by shrimp ponds increased from 2450 ha to 175,748 ha, an increase of 7073%. During the same period, mangrove cover in Ecuador decreased by 56,395.9 ha, representing a loss of 27.7% (CLIRSEN and PMRC 2007).

In fact, many shrimp ponds were built or expanded illegally. Ecuador's Undersecretariat of Aquaculture estimated that, in 2013, 66% (6192 ha) of shrimp ponds in Esmeraldas province were illegal. Similarly, in the provinces of El Oro, Manabí, and Guayas, illegal shrimp farms accounted for 59% (8434 ha), 39% (12,576 ha), and 18% (17,437 ha), respectively (Gobierno de la República del Ecuador 2008).

Even within the protected areas, shrimp ponds were built. The Undersecretariat of Marine and Coastal Management (SGMC) determined that in four coastal protected areas that belong to the National System of Protected Areas, shrimp farms were built or expanded after the date of the creation of the protected área.

To reduce the impacts of this activity, Executive Decrees No. 1391 (Gobierno de la República del Ecuador 2008) was approved, establishing that shrimp ponds created after 1999 are illegal because they occupy areas that belong to the State or are located within protected areas. Based on these Executive Decrees, between 2010 and 2012, 40 shrimp ponds occupying 2495 ha were evicted. This decree also established as a condition for shrimp companies to regularize the reforestation of their areas within 1 year. Shrimp companies, in compliance with Decree No. 1391 reforested 3545.85 ha by October 2012 (Ministerio del Ambiente del Ecuador 2017b), however, there is no concordance between the number of hectares of mangrove deforested and hectares reforested.

Between 1995 and 2016 there was a recovery of almost 15,000 ha of mangrove forest, increasing the area to 161,000 ha. This mangrove coverage gain was the result of reforestation programs implemented by different institutions and communities with Agreements of Sustainable Use and Custody of Mangroves, as well as the natural regeneration of the ecosystem.

The Organic Environmental Code-CODA (approved in 2017) establishes that shrimp companies that destroy the mangrove (by logging, pollution, impeding tidal flow to the mangroves, etc.) will be fined and have their permits revoked. Fines resulting from these sanctions will go to the Fondo Nacional para la Gestión Ambiental (National Fund for Environmental Management).

In 2014, the Ministry of Environment conducted a study to identify sites with potential for mangrove reforestation on the Ecuadorian mainland. A total of 538 sites with denuded or semi-denuded soil were identified. However, approximately 72% are located within areas used for shrimp farming. Sixty-six sites were selected, representing approximately 1604 ha, with soils and potential conditions to initiate natural regeneration or reforestation processes of the mangrove ecosystem. Of these, 18 sites are in the province of Guayas, representing about 1179 ha (74%). The remaining 48 sites are scattered throughout the Cayapas - Mataje Mangrove Ecological Reserve (Esmeraldas province). No sites with regeneration or reforestation potential were identified in the province of El Oro (Astudillo et al. 2014). This means that in Ecuador, there are few spaces available for reforestation or afforestation of mangroves.

19.8 Global Change and Its Effect on Mangroves

It is known that climate change will have a series of impacts on the mangrove ecosystem. Sea-level rise may be the greatest threat to mangroves of all the climate change outcomes. Changes in sea level would alter flooding patterns and the structure and areal extent of mangroves (Gilman et al. 2008). Other important threats to mangroves from climate change include:

- Extreme high water events. Increased levels and frequency of extreme high water events may affect the position and health of mangroves through altered sediment elevation and sulfide soil toxicity. This sedimentation varies by mangrove species and their root type (USGS 2004). The frequency of extreme high water events is projected to increase by factors such as El Niño Southern Oscillation (Gilman et al. 2008).
- Storms. The increased intensity and frequency of storms has the potential to increase damage to mangroves through defoliation and tree mortality. These events can also alter the mangrove sediment elevation through soil erosion and deposition, the sedimentation varies by mangrove species and their root type (Gilman et al. 2008).
- Precipitation. Changes in precipitation patterns are expected to affect mangrove growth and spatial distribution. Areas with decreased precipitation will have a smaller water input to groundwater and less freshwater surface water input to mangroves, increasing salinity (Field 1995).
- Temperature. Increased surface temperature is expected to affect mangroves by changing species composition, changing phenological patterns (e.g., timing of flowering and fruiting); increasing mangrove productivity where temperature does not exceed an upper threshold; and expanding mangrove ranges to higher latitudes (Gilman et al. 2008).

- Atmospheric CO_2 concentration. Elevated CO_2 concentration may increase mangrove growth by stimulating photosynthesis or improving water use efficiency (Gilman et al. 2008).

19.8.1 El Niño Southern Oscillation

El Niño Southern Oscillation (ENSO) is a global climatic event that causes the warming of sea waters and leads to heavy flooding and drought in different countries around the world. This climate phenomenon causes important modifications in coastal environments and in mangroves in particular. In Ecuador, there is little research on the effects that this climatic event has had on mangroves. However, an important reference is the studies carried out in the mangroves of Tumbes (Peru) since they are part of the same ecoregion of the province of El Oro and the Gulf of Guayaquil:

- Decrease in salinity due to the contribution of freshwater from rainfall, particularly in the areas located at the mouths of the rivers. Although normally during the rainy season (January to May) salinity drops by more than 10 units, during ENSO events salinity decreased by up to 30 units, as a result of abundant freshwater entering the mangroves. Low salinity for long periods can interfere with the development and growth of *Rhizophora mangle* and *R. harrisonni* species (as they need and are tolerant to high salinity levels) and the molluscs and crustaceans that depend on the habitat of these species, particularly the black shell (*Anadara tuberculosa* and *A. similis*) and red crab (*Ucides occidentalis*) (Ministerio del Ambiente e Instituto Geofísico del Perú 2017).
- Increased river erosion and sediments. These are deposited in the mangrove swamps, clogging the estuaries, another factor that decreases salinity levels. This caused a phenomenon known as “osmotic shock,” which is characterized by the slow development and, in some cases, the death of mangroves, crustaceans and molluscs (*Anadara tuberculosa*). Morera et al. (2017) determined that rains such as those that occurred during extreme El Niño events increased the erosion rate of rivers by up to 20 times their average. To calculate erosion, Morera et al. (2017) used the Suspended Sediment Yield (SSY) as an indicator, which, in Peru, between 1968 and 2012, increased 3 to 60 times compared to normal years.

The most recent study on the effects of climate change on sea levels and its influence on water level rise in coastal areas has been developed by the Climate Central (2021) organization. This study determined that three coastal areas of Ecuador are at risk of disappearing by 2050: the Gulf of Guayaquil, the coastal profile of Esmeraldas and El Oro. The three areas at risk are precisely those that contain almost all of Ecuador’s mangrove forests.

– The Gulf of Guayaquil is one of the areas that would be affected by flooding until 2050. Punta Miel, La Unión, El Guasmo and part of Puná Island are the

Guayaquil localities that could disappear due to the increase in the level of the waters of the Pacific. According to projections, in Punta Miel, the floods would devastate a total area of 210 km^2.
– The province of El Oro. The entire coastal zone of this province will be affected by flooding. Puerto Bolívar and Puerto Jelí will disappear by 2050. These are two of the three most important artisanal fishing ports in this province.
– The province of Esmeraldas. In this province, an area of 40 km^2 of coastline would disappear and almost two thirds of the Muisne canton would be lost.

19.9 Livelihoods

Before shrimp farming was developed, the subsistence economy of coastal inhabitants was based on the traditional use of mangrove forests as harvesting for mollusc and crustacean and charcoal production. The communities with mangrove concessions depend on the extraction of mangrove resources, including crabs, cockle shell, oyster, mussels, shrimp, and different species of fish, for food and protein and their livelihoods with the main resources being red crab (*Ucides occidentales*) and black shell or black cockle (*Anadara tuberculosa*) (Darquea 2016) (Fig. 19.3).

In Ecuador, the red crab (*Ucides occidentalis*) is the most commercially important crustacean. In the Gulf of Guayaquil, more than 2215 fishers extract approximately 11 million crabs per year, contributing USD $16 million to the Ecuadorian Gross Domestic Product GDP (USAID 2012). Although another research conducted by the National Fisheries Institute (INP) estimated that at least 16 million crabs are caught in the Gulf of Guayaquil every year. This means that more than 9000 people have red crab as their main economic livelihood (Zambrano and Solano 2018).

The second most important mangrove resource for local communities is the black shell *Anadara tuberculosa*. In Ecuador, this mollusc is present mainly in the provinces of El Oro and Esmeraldas and is harvested for subsistence and commercial markets. *A. tuberculosa* constitutes the basis of the food diet and source of economic support for some 4000 families in Ecuador that depend directly on the mangrove ecosystems. Although the contribution of this mangrove mollusc to the Ecuadorian Gross Domestic Product is small compared with larger commercial sectors like bananas and shrimp, the production and commercialization of *A. tuberculosa* have great potential to satisfy the internal demand of Ecuador. El Oro and Esmeraldas provinces are the most important black shell capture areas in Ecuador (Prado-Carpio et al. 2019).

Throughout the coast, there has been a decrease in the volume of fishing and harvesting of aquatic species. Regarding the red crab (*Ucides occidentalis*), in 2010, 7,687,682 crabs were collected while in 2013 it was reduced to 5,017,194 (Mora and Moreno 2008). The reduction in the collection of black shell (*Anadara tuberculosa* and *A. similis*) can be seen by the information provided by the National Fisheries Institute (INP), which reports that in 2004, 26,000,000 black shell were collected in six of the country's main fishing ports, while 20 years ago (1984), more than

Fig. 19.3 The collection of black shell (*Anadara tuberculosa*) and red crab (*Ucides occidentalis*) are the most important economic and livelihood activities for thousands of artisanal fishermen in Ecuador

34,000,000 black shell were collected (Yllescas et al. 2009). The scarcity of the mollusc has important socioeconomic impacts. Currently, shellfish harvesters have had to extend their workday from 4 to 8 h to reach at least 100 shells per day, when they used to catch 700 to 1000 shells per day.

19.10 Threats and Conservation

Although mangroves are one of the most productive ecosystems in the world, they are also one of the most threatened. Anthropogenic activities are the main drivers of mangrove destruction and are similar in almost all countries (Spalding et al. 2010). These types of activities substantially alter the composition, structure, and function of mangroves, reducing the ecosystem services they provide. Globally, it is estimated that 35% of mangrove forests have been lost, a situation that is not much different in Ecuador. While globally it is considered that less than 1% of the remaining tropical forests are mangroves, in Ecuador, this ecosystem represents 4%.

The mangrove swamp in Ecuador is located mainly in six estuaries. CLIRSEN and PMRC (2007) determined that in 1969 the mangrove area in Ecuador reached

203,624 ha, which, by 2006, was reduced to 146,971 ha, a loss of 56,653 ha, equivalent to 27.6%. The estuaries that lost the highest amount of mangroves as a result of shrimp farming were: Cojimíes (79.1%), Chone (76.5%), and the Jambelí Archipelago (56.2%).

The highest annual rate of deforestation occurred between 1991 and 1995 (2.35% per year). However, between 1995 and 1999 a recovery of the mangrove cover was observed and then between 1999 and 2006, the annual rate of deforestation was 0.13%. According to the Ministry of Environment, in the decade from 2006 to 2016, a mangrove recovery of 14,864 ha was observed (Table 19.2).

The current mangrove area in Ecuador is 161,835 ha. This mangrove coverage gain was the result of reforestation programs implemented by different institutions and communities that have mangrove use and custody agreements, as well as the natural regeneration of the ecosystem (Ministerio del Ambiente del Ecuador 2017a, b, c).

The transformation of the mangrove into shrimp ponds and urban development are the main factors in the loss of the mangrove ecosystem in Ecuador.

Urban Development

Many coastal cities are located in areas that were once occupied by mangroves. It is estimated that in 1994 approximately 3000–5000 ha of mangroves were destroyed to make way for the growth of cities such as Guayaquil, Machala, and Esmeraldas. The area in which Guayaquil is located was originally an extensive mangrove area. In this city, in the 1950s, large numbers of migrants from various cities in Ecuador settled mostly in suburban areas, mainly composed of mangroves, which were cut down and subsequently filled in for the construction of irregular housing. The mangroves were cut to be used for housing construction and conversion to charcoal (Poveda and Avilés 2018).

Shrimp Farming

Shrimp farming is considered the main cause of mangrove deforestation in Ecuador, which is carried out for the construction of ponds for the cultivation of shrimp (*Litopenaeus vannamei*) Fig. 19.4.

Since the construction of the first shrimp ponds in the 1960s, Ecuador has become one of the main producers of farmed shrimp in the world. (Latorre 2014). Between 1979 and 1984, shrimp production had a significant increase which reached 36,600 Metric Tons (MT), with exports valued at US$183,000,000. In 2018, production increased to 506,000 MT, which exceeded US$3,200,000,000 in exports. In 2020 Ecuador exported US$3,823,530,000 (608,000 MT). Between 2017 and 2018, shrimp was the first non-oil export product (Cámara Nacional de Acuacultura 2021) (Fig. 19.5).

According to the National Chamber of Aquaculture of Ecuador, in 2015 there were 213,000 ha allocated to shrimp production, of which 181,000 ha are located in an area that was originally mangrove. The province of Guayas has the largest cultivation activity of this crustacean, with approximately 140,000 ha, representing 66% of total production (Cámara Nacional de Acuacultura 2021).

Table 19.2 Mangrove loss by estuary (in hectares). Period 1969–2006

Estuaries	1969	1984	1987	1991	1995	1999	2006	% of mangrove lost compared to 1969
Cayapas Mataje	23,677	23,653	23,507	22,863	21,947	22,057	21,400	9.6
Muisne	3282	2701	2445	1340	830	1187	1187	52.5
Cojimíes	13,123	9917	8466	6028	3651	1921	2742	79.1
Chone	3973	1673	1040	784	391	705	932	76.5
Guayaquils gulf	124,320	119,277	115,784	109,608	102,108	104,715	105,130	15.4
Jambelí archipelago	34,712	24,592	23,570	21,092	17,697	19,111	19,111	56.2
Total	203,624	181,815	174,815	161,718	146,628	149,699	146,971	27.6

Source: CLIRSEN and PMRC (2007)

Fig. 19.4 In Ecuador and other tropical countries, shrimp farms have been developed at the expense of mangrove forests, which are cleared for the establishment of shrimp ponds. In addition to the direct loss of mangroves during construction, shrimp farms also impact the adjacent mangroves through the release of large quantities of antibiotics, pesticides, fungicides, parasiticides, and algaecides, as well as antibiotics. Source: Molnar et al. (2013)

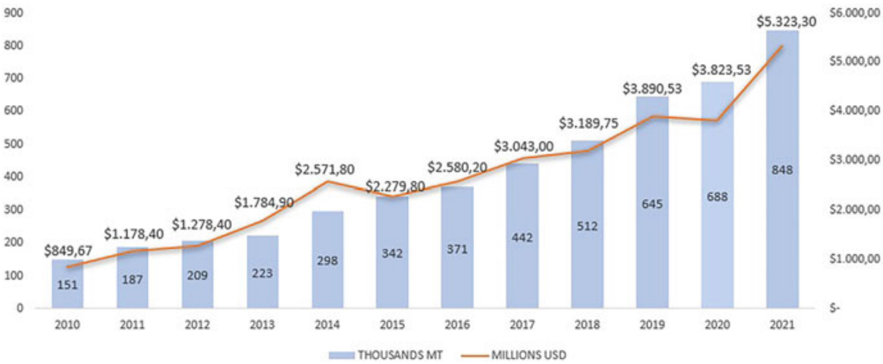

Fig. 19.5 The growth of the shrimp industry has been progressive since its beginnings in the 1960s. Source: Cámara Nacional de Acuacultura (2021). One MT = 1000 kg

In addition to mangrove clearing, during shrimp farming, effluents rich in organic and inorganic particles are also released which deteriorate estuarine resources, particularly sediments (shell and crab habitat) and water (Hurtado and Rodríguez 2012).

19.11 Conservation

In Ecuador, all mangrove forests are the property of the State, with the Ministry of the Environment (MAE) being the institution responsible for their management. Mangroves are out of commerce, not susceptible of possession or any other means of appropriation (CODA 2017).

In response to the destruction of the mangrove ecosystem, several strategies have emerged in the country for its conservation and sustainable use, which protect 100% of the mangrove swamp:

- National System of Protected Areas (SNAP).
- Protective Forest (ABVP).
- Agreements of Sustainable Use and Custody of Mangroves Ecosystem (AUSCEM).

The mangrove area under AUSCEM is almost equal to that occupied by the protected areas of the National System of Protected Areas (SNAP) which shows the importance of this conservation strategy (Table 19.3).

19.11.1 State Protected Areas (SNAP)

The importance of marine and coastal ecosystems for Ecuador and the services they provide to its inhabitants were recognized more than 80 years ago. It is not a coincidence then that the first protected area created in Ecuador was located in marine and coastal environments: the Galapagos Islands. Ecuador's first action to protect these islands was through an Executive Decree issued by the Government in 1934, which aimed to protect some species and control access of ships to the Galapagos Islands, and in 1959 it declared them a National Park. The following

Table 19.3 Mangrove distribution according to the conservation strategy

Conservation strategy	Coverage (ha)	%
Protected Areas (SNAP) (2020)	72,523	45.15
Agreements of Sustainable Use and Custody of Mangroves (2020)	69,369.48	42.86
Protective Forest (2020)	19,943	11.99
Total	161,835	100

Source: www.ambiente.gob.ec

Table 19.4 State Protected Areas with partial or total mangrove coverage

	Protected area	Month/year it was created protected area	Total extension (ha)
1	Manglares Churute Ecological Reserve	July 1979	49,389
2	Cayapas Mataje Ecological Reserve	October 1995	51,300
3	Ecological Reserve Arenillas	May 2001	13,170
4	Islas Corazón y Fragatas Wildlife Refuge	October 2002	2811
5	Manglares El Salado Wildlife Refuge	November 2002	10,635
6	Manglares Estuario del Río Muisne Wildlife Refuge	March 2003	3173
7	Manglares El Morro Wildlife Refuge	September 2007	10,030
8	Wildlife Refuge Estuario del Río Esmeraldas	June 2008	242
9	National Recreation Area Isla Santay	February 2010	2215

Source: Bravo et al. (2016)

coastal marine protected areas were created in 1979: the Manglares Churute Ecological Reserve and the Machalilla National Park. Since then, there has been a constant growth in the surface area of Marine Coastal Protected Areas (MCPAs). Between 2008 and 2015, areas with extensions exceeding 100,000 ha were created (Fundación Futuro Latinoamericana 2011). The most recent was the Bajo Copé Marine Reserve. Today, Ecuador has 19 marine and coastal protected areas, which together represent about 8% of the total coverage of the SNAP.

In 2017 the Network of Marine and Coastal Protected Areas of Ecuador was created, as a mechanism for political-administrative interaction to enhance institutional resources and manage the areas in an articulated and synergistic manner. The aim of this network is to guarantee biological connectivity between ecosystems by creating connectivity corridors and conserving the biodiversity of the National System of Protected Areas in the marine coastal zone (Ministerio del Ambiente del Ecuador 2017c).

The first protected area established with mangrove ecosystem was the Manglares Churute Ecological Reserve (Guayas province). With an area of 51,300 ha, Cayapas Mataje is the protected area of Ecuador with the largest amount of mangrove. The most recent protected area with mangrove ecosystem, the Area Nacional de Recreación Isla Santay, was created in 2010. Nine protected areas contain totally or partially mangroves, which in total comprise 72,523 ha (Table 19.4).

The largest number of mangrove protected areas are located in the Gulf of Guayaquil, although the largest area, Cayapas Mataje Ecological Reserve, is in the north of Ecuador, in the province of Esmeraldas. The second largest protected area, Manglares Churute Ecological Reserve, is located in the Gulf of Guayaquil (Fig. 19.6).

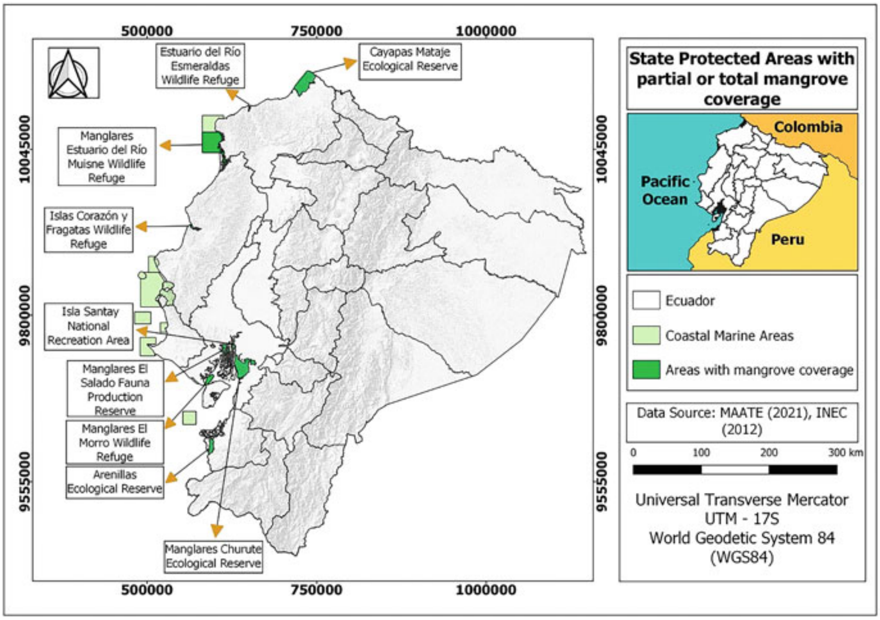

Fig. 19.6 Protected Mangrove areas in Ecuador

19.11.2 Agreements of Sustainable Use and Custody of the Mangrove Ecosystem (AUSCEM)

The AUSCEM are the management tools contemplated in the Ecuadorian legal framework (CODA 2017), under which mangrove forests are handed over to ancestral users to custody these areas. Promoted by community organizations and NGOs since the early 1980s, these agreements were formalized in 1999 through the issuance of Executive Decree No. 1102 and regulated through Ministerial Agreement No. 172 of 2000. The AUSCEM guarantee the "custodians" exclusive access to the mangrove areas with the right to sustainably use bioaquatic resources, but in turn have the obligation to realize control and surveillance of mangrove and report the progress of its management to the Ministry of Environment (CODA 2017). Approximately 7000 families benefit from these agreements. The AUSCEM, also called "mangrove concessions," are important because they protect 42.85% of the Ecuadorian mangrove (almost the same extent as the protected areas). In the province of El Oro, the AUSCEM cover about 82.3% (15,636 ha) of this ecosystem. The AUSCEM are now included in the Organic Code on the Environment (CODA) which came into force in 2018; this means better legal protection for these custody áreas (López-Rodríguez et al. 2019).

Article 266 of the Organic Environmental Code allows the following activities in the AUSCEM:

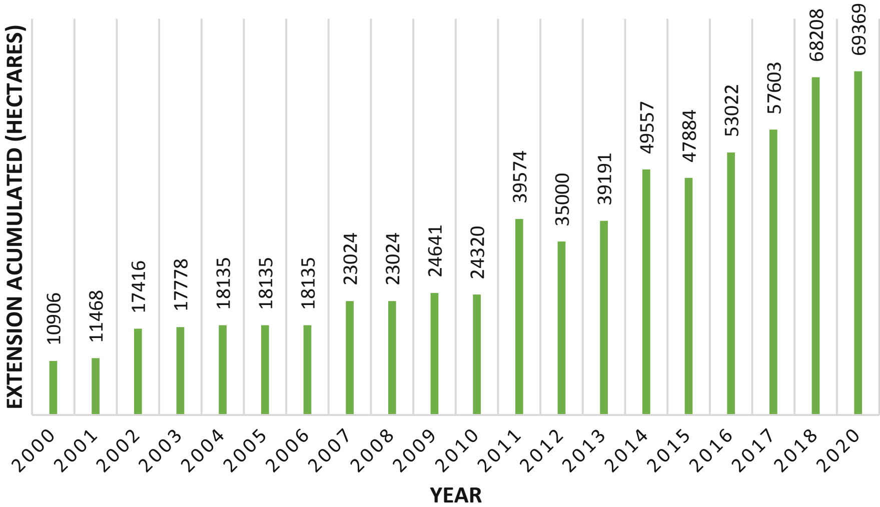

Fig. 19.7 Evolution of the Agreements of Sustainable Use and Custody of the Mangrove Ecosystem in ha of mangrove by year

(a) Sustainable harvesting of traditional species of commercial interest;
(b) Mangrove restoration;
(c) Tourism and activities of recreation no destructive of the mangrove;
(d) Conservation and protection; and.
(e) Education and scientific research.

Currently, in Ecuador, there are community organizations that have stewardship agreements covering more than 69,369 ha (Fig. 19.7). Since 2000 there has been a permanent growth in the delivery of custody agreements. Only in 2012 and 2015 there was a decrease.

19.11.3 Socio Manglar, Incentive for Mangrove Conservation

Socio Manglar is a mangrove conservation incentive which was created in 2014 to support the management of the Agreements of Sustainable Use and Custody of the Mangrove Ecosystem (AUSCEM). In 2021, there were 25 signed agreements covering 37,678 ha, for which they receive USD 420,144 each year, with which 1635 families benefit (Ministerio del Ambiente del Ecuador 2020).

- *Protective forests*

  In 1986, the entire mangrove was classified as a protective forest, providing governmental institutions with a basic set of instruments to punish its deforestation. Ministerial Agreement No. 498 of 1986 establishes that “mangroves, even those existing in private properties, are considered State property and are out of commerce, are not susceptible to possession or any other means of appropriation and may only be exploited by means of a concession granted in accordance with this Law and its Regulations." Under this Ministerial Agreement, the entire mangrove forest in Ecuadorian territory was legally protected as a protective forest. Later, in 1994, a mangrove deforestation ban was established, and the expansion and construction of new shrimp ponds was prohibited.

However, even though the laws forbid deforestation and degradation of protected areas, the mangrove coverage reduced even in recent years (2010–2018) by 15,034 ha due to conversion to shrimp farms, which shows a weakness in the control, surveillance and monitoring of these areas and an illegality on the part of the shrimp farms (López-Rodríguez 2018).

19.11.4 International Categories

19.11.4.1 Ramsar Sites

There are 19 sites designated as Wetlands of International Importance (Ramsar Sites) in the country comprising an area of 1,064,483 ha (Ramsar Covention 2021). Seven correspond to marine and coastal ecosystems of which, four contain mangrove (totally or partially). Manglares "Don Goyo" is the only Ramsar Site that does not belong to the National System of Protected Areas, however, is part of several AUSCEM of the province of Guayas. Isla Santay was declared a National Recreation Area in 2010, 10 years after it was included in the Ramsar List (Table 19.5).

19.11.4.2 Important Bird Areas (IBA)

In Ecuador, 107 IBAs have been recognized, of which 99 are located on the mainland or are continental islands and 10 are in the island region of Galapagos. The IBAs cover an area of 91,435 km^2, corresponding to 35.7% of the total area of

Table 19.5 Coastal marine Ramsar sites in Ecuador

Ramsar site	Year	Extension (ha)
Marine Zone of the Machalilla Nacional Park	1990	14,430
[a]Isla Santay National Recreation Area	2000	4705
[a]Humedales del Sur de Isabela (Parque Nacional Galápagos)	2002	872
Isla Santa Clara Wildlife Refuge (now is Marine Reserve)	2002	46
[a]Manglares Churute Ecological Reserve	2003	35,042
Cayapas- Mataje Ecological Reserve	2003	44,847
[a]Manglares del Estuario Interior del Golfo de Guayaquil "Don Goyo"	2012	15,338

Source: Ramsar Covention (2021)
[a]Ramsar Sites with mangrove

Table 19.6 IBAs containing mangroves

Name of the IBA	Location (province)	Area (ha)	Conservation category
Mataje-Cayapas-Santiago	Esmeraldas	70,000	Protected area (SNAP)
Isla Santay	Guayas	4705	Protected area (SNAP)
Churute Ecological Reserve	Guayas	49,984	Protected area (SNAP)
Mangroves of the Gulf of Guayaquil	Guayas	200,000	Mangrove concessions (AUSCEM) and SNAP
Archipelago of Jambelí	El Oro	30,000	Mangrove concessions (AUSCEM)
Arenillas Ecological Reserve	El Oro	17,082	Protected area (SNAP)
Humedales del Sur de Isabela (Galápagos National Park)	Galápagos	872	Protected area (SNAP)

Source: Santander et al. (2005)

the country. The most extensive IBA is Manglares del Golfo de Guayaquil, with 200,000 ha, which includes the El Salado Mangrove Fauna Production Reserve (3700 ha), mangrove areas within the city of Guayaquil and several AUSCEM. Seven IBAs fully or partially contain mangroves (Santander et al. 2005) (Table 19.6).

19.12 Case Study. Management Effectiveness of Agrements of Sustainable Use and Mangrove in the Province of El Oro

Management effectiveness evaluations are very important because they provide insight into the levels of management of protected areas or other area-based conservation measures and allow for timely corrective action. In addition to understanding management problems and their causes, these evaluations make it possible to identify and apply, in a timely manner, strategies, and measures to improve management and conservation.

In Ecuador, the methodology most commonly used to evaluate the effectiveness of management in coastal marine areas has been the Hockings Reference Framework proposed by IUCN (Hocking et al. 2000) and the 360° performance evaluation (Coello et al. 2008).

In the province of El Oro there are 15,636 ha of mangrove under AUSCEM given to 23 fishermen associations. Considering the mangrove extension in El Oro province, which is 19,318.39 ha, the mangrove protected in the custody areas is 81%. The AUSCEM in this province are extremely important.

As part of the project "Integrated Management of Marine and Coastal Spaces of High Value for Biodiversity in Continental Ecuador," of the Ministry of Environment and Conservation International, the analysis of management effectiveness of the AUSCEMs of the province of El Oro was conducted in 2017 (López-Rodríguez et al. 2019). This research analyzed the management effectiveness of 20 organizations' Agreements of Sustainable Use and Custody of Mangroves (AUSCEM) using the 360° Performance Evaluation with 17 indicators distributed in four categories:

- Mangrove Conservation Status. Evaluates aspects such as mangrove cover and contamination.
- Performance of entities that support organizations with AUSCEM. Includes institutions such as the Ministry of Environment, Undersecretariat of Marine and Coastal Management (currently eliminated), other State institutions, universities, etc.
- Compliance with the agreement (AUSCEM). Includes compliance with the Management Plan, elaboration of biannual reports, and complaints, etc.
- Performance of the organization. Includes compliance with the implementation of control and surveillance programs, sustainable use, participation of partners, economic contributions, commercialization, etc.

The following activities were carried out to gather the information:

- Review of AUSCEM documentation.
- Focus groups with delegates from each organization to learn about their perceptions of the AUSCEM.
- Interviews with representatives of the organizations.
- Interviews with other stakeholders (Ministry of Environment, technical assistance entities, NGOs, Universities, etc.).

For the scoring and weighting of this evaluation, a Likert scale was used with four rating levels (from 0 to 4) associated with a percentage reflecting the respective management levels, which was adapted from the methodology originally used by De Faría (1993) and later incorporated by WWF, GIZ and IUCN in the Manual for Evaluating the Effectiveness of Protected Area Management (Cifuentes and Izurieta 2000).

Levels of management effectiveness:

Level I Unsatisfactory management (≤25%). It indicates that the area lacks the minimum resources necessary for its basic management and, therefore, there are no guarantees for its long-term permanence.

Level II Slightly satisfactory management (26–50%). The area possesses certain resources and means that are indispensable for its management, but it lacks many elements to reach a minimum acceptable level, so its long-term permanence is not guaranteed.

Level III Satisfactory management (51–75%). The area has the minimum elements for management, but there are still deficiencies that do not allow the establishment of a solid basis for effective management.

Level IV Very satisfactory management (76–100%). The factors and means that make management possible are adequately addressed. The permanence of the area

Table 19.7 Averages of the indicators of the 20 organizations with AUSCEM

	Analysis of management effectiveness factors	Mangrove coverage	Pollution	Total mangrove conservation status	Relationship SGMC—organizations	Support from the technical assistance organization	Support from governmental organizations	Support from other organizations	Mangrove partner	Total performance entities that support auscem	Compliance management plan	Semiannual reports
1	"10 DE AGOSTO"	4	3	3.5	3	3	3	2	0	2.2	4	2
2	"LAS HUACAS"	4	3	3.5	4	4	4	4	4	4	4	4
3	"ESTERO PORTEÑO"	4	2	3	3	3	3	4	0	2.6	4	4
4	"LOS ISLEÑOS"	4	2	3	3	2	3	3	4	3	3	3
5	"AMOR Y ESPERANZA"	4	2	3	4	4	3	4	4	3.8	3	1
6	"SAN ANTONIO"	4	2	3	3	3	2	2	4	2.8	2	4
7	"19 DE OCTUBRE"	4	3	3.5	3	2	2	2	4	2.6	2	2
8	"LOS PRECIADOS"	4	2	3	3	2	2	2	4	2.6	2	2
9	"MAR DE GALILEA"	4	3	3.5	3	2	2	2	0	1.8	**2**	0
10	"RÍO CHAGUANA"	4	3	3.5	3	2	2	2	4	2.6	2	4
11	"NI UN PASO ATRÁS"	4	3	3.5	4	2	2	2	4	2.8	2	2
12	"24 DE OCTUBRE" – ARMA	4	3	3.5	4	2	2	3	0	2.2	1	1
13	"11 DE ENERO"	4	3	3.5	3	2	3	2	4	2.8	1	1
14	"PUERTO GRANDE"	4	3	3.5	4	3	3	3	4	3.4	1	1
15	"17 DE ENERO"	4	3	3.5	3	2	2	2	0	1.8	1	2
16	"16 DE JULIO"	4	2	3	2	2	2	2	0	1.6	1	3
17	"ISLA PONGALILLO"	4	3	3.5	3	4	2	3	4	3.2	4	2
18	"ISLA BELLAVISTA"	4	3	3.5	3	2	2	2	0	1.8	1	1
19	"COSTA RICA"	4	3	3.5	3	2	2	2	0	1.8	1	0
20	"VIKINGOS DEL MAR"	4	2	3	3	2	2	2	0	1.8	2	1
	Management effectiveness by subject of the agreement	4.0	2.7	3.3	3.2	2.5	2.4	2.5	2.2	2.6	2.2	2.0

(continued)

Table 19.7 (continued)

Complaints	Total compliance with agreement	Contribution $ per member	Training, dissemination, awareness raising	Partner involvement and leadership	Days invested in Control and Surveillance	Control and surveillance system	Compliance with fishing regulations (%)	Direct sales, value added, diversification	Total custodian performance	Total average agreement	Total average agreement (%)
4	3.3	1	3	1	2	4	4	0	2.1	2.6	**65**
4	4.0	4	4	4	4	4	4	2	3.7	3.7	**93**
4	4.0	1	4	4	2	2	2	4	2.7	2.8	**69**
4	3.3	3	4	4	4	3	4	2	3.4	3.1	**79**
4	2.7	2	4	4	3	3	2	4	3.1	3.3	**83**
4	3.3	2	3	3	2	3	0	3	2.3	2.7	**67**
2	2.1	2	2	3	4	3	2	0	2.3	2.8	**70**
4	2.8	3	2	1	2	3	0	1	1.7	2.4	**61**
4	2.1	2	2	1	3	3	0	0	1.6	2.3	**57**
2	2.6	2	2	2	1	3	0	0	1.4	2.5	**63**
2	2.0	2	2	1	2	3	0	0	1.4	2.6	**64**
4	2.0	2	3	2	1	2	2	3	2.1	2.6	**65**
2	1.3	3	2	3	4	2	0	0	2.0	2.8	**69**
2	1.3	3	4	4	4	3	4	4	3.7	3.5	**88**
2	1.7	2	2	1	1	2	0	0	1.1	2.1	**54**
4	2.7	2	2	1	1	1	0	0	1.0	1.9	**47**
4	3.3	3	4	4	2	4	4	0	3.0	3.2	**81**
4	2.1	2	4	3	2	2	4	1	2.6	2.6	**66**
4	1.8	0	4	3	2	2	4	1	2.3	2.5	**63**
4	2.4	3	3	3	3	3	4	0	2.7	2.5	**63**
3.4	2.5	2.2	3.0	2.6	2.5	2.8	2.0	1.3	2.3	2.7	**68**

would be guaranteed because there is a dynamic balance between the fundamental elements of management.

19.12.1 Results

The results indicate that the management effectiveness of the 20 organizations analyzed ranges between 46.7% and 93.5%, which means that no organization has an Unsatisfactory Management level. Only three custody areas were at the low Satisfactory level (41–60%), 13 have a Satisfactory Level (61–80%) and four custody areas reached the Very Satisfactory Management Level (81% and 100%) (Table 19.7).

Regarding the indicators, the lowest corresponds to the group on "Performance of support entities" which refers to the support fishers' organizations receive from the Ministry of Environment, local governments, universities, NGOs, and other organizations. At the individual indicator level, the lowest corresponds to "Direct sale/ value added," which shows that most fishers still work with intermediaries who are in charge of marketing bioaquatic products.

19.12.2 Mangrove Conservation Status

An important indicator of AUSCEM management is the coverage of mangroves. The perception of the organizations, institutions, and stakeholders is that massive mangrove deforestation has stopped since the creation of the AUSCEMs, although it occurs on a low scale, mainly in the areas adjacent to shrimp ponds. On the other hand, they perceive a mangrove recovery in sites far from shrimp farms and attribute this recovery to the control and surveillance activities and reforestation carried out by the organizations. Perceptions of mangrove recovery were verified through a multi-temporal analysis in three periods: 1998–2010–2017. In all areas there was an increase in vegetation cover. In terms of pollution, the main causes are waste from shrimp farms, agrochemicals produced in banana activity, wastewater from cities, garbage that reaches estuaries and mangroves; mining and fuel spills from boats, among other factors (UTPL 2017).

19.12.3 Performance of Entities that Support Organizations with AUSCEM

This group presents indicators with high values. The organizations acknowledge the support of the Ministry of Environment, local governments, NGOs, and universities.

A requirement for organizations to sign an AUSCEM is to have a technical assistance entity; the objective is to guarantee the necessary technical support for the implementation of the management plan and other activities that contribute to the management of the custody area. The perception of technical support varies between 15% and 85% by the organizations that have AUSCEM and 45% to 95% of the technical support entities.

19.12.4 Compliance of the Organizations with AUSCEM

According to the Ministerial Agreement No. 129 of August 11, 2010, the organizations have the obligation to implement Management Plans for their areas. The perception of the implementation of the plans varies between 25% and 85%. Reasons for non-compliance include lack of budget and activities that are not aligned with the reality and interests of the organization. According to the same Agreement, organizations with AUSCEM must submit biannual reports on the management plan. In this context, it was determined that 18 organizations complied with the delivery of these reports, 9 of them with a "satisfactory" acceptance and only two organizations did not deliver any report. Likewise, the organizations have the obligation to protect the mangroves in their areas from any aggression, destruction, or damage, and to report irregularities to the environmental authority. The organizations mentioned that they have made written, verbal, and telephone complaints and notifications, but they stopped doing so because they did not receive a response from the authorities.

19.12.5 Performance of the Organizations with AUSCEM

In Ministerial Agreement No. 144 of 2011, it is established that each Management Plan must have three programs: Control and Surveillance, Sustainable Use, and Monitoring. Regarding "control and vigilance," all organizations stated that they patrol their areas of custody. Regarding "sustainable harvesting", the organizations apply several measures.

In addition to those established by national regulations (such as minimum sizes of 45 mm for black shell and 70 mm for red crab), they apply voluntary measures, such as self-closures, fewer days of shell and crab extraction, rotation of extraction zones, among others. Direct commercialization and added value to their products" and "compliance with fishing regulations" are the lowest indicators in this group. The indicator "Training, dissemination and awareness-raising" reached the maximum score due to the presence of important international cooperation projects and the support of universities.

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Chapter 20
Mangroves of Brazil

Luiz Drude de Lacerda, Alexander C. Ferreira, Rebecca Borges, and Raymond Ward

Abstract Brazil has the third mangrove extension in the world, occupying around one million hectares. These forests occur along almost the entire Brazilian coast but are unevenly distributed, showing distinct biological and ecological characteristics, depending on climate, fluvial contribution, and littoral geomorphology. Most extensive forests are in the north region, including the higher continuous mangrove fringe of the planet. Fossils of mangroves appear in the Paleocene of Brazil, but modern genera appeared in the Eocene and Miocene. More than 100 plant species appear associated to mangroves, which also host a great variety of invertebrates and vertebrates (around 600 species) and microorganisms. Mangroves provide many goods (fisheries, timber, and other products) and services (biodiversity conservation, fisheries breeding areas, coastal protection, carbon sequestering), mostly relative to their extent, compared to other Brazilian biomes. Mangrove ecosystems stock large amounts of carbon above and below ground, but biomass, productivity, and carbon allocation vary widely among Brazilian mangroves and are dependent on latitude, climate, and geomorphology. Despite categorized as protected areas, Brazilian mangroves suffer several impacts and permanent attempts to setback protective legislation. Direct (deforestation, pollution, occupation, aquaculture) and indirect (climate change) human pressures are sources of mangrove degradation and mortality. Climate change impacts, mainly sea level rise, decrease in rainfalls and intensification of droughts are presently threatening mangroves, at the northeastern and southeastern sectors of the Brazilian coast. Conservation of present stands and rehabilitation of degraded areas are a significant and urgent measures to continuing

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providing mangrove goods and services and help mitigate further impacts form climate change.

Keywords Biodiversity · Conservation · Ecosystems · Forest structure · Anthropogenic impact · Coastal management · Climate change

20.1 Physical Attributes and Characteristics

20.1.1 Extension of Mangroves in Brazil

The Brazilian coast extends over 7367 km along the Atlantic Ocean roughly divided into at least four large sectors or Large Marine Ecosystems (LME), with common environmental characteristics (Lacerda et al. 1993; Knoppers et al. 1999). Mangroves occur along almost the entire Brazilian coast, in three of the large sectors (Fig. 20.1). Forests, however, are unevenly distributed along the coast and present distinct biological and ecological characteristics, depending on climate, fluvial contribution, and the geomorphology of the littoral (Hueck 1972).

The North Quaternary coast is subdivided according to climate, fluvial contribution, and continental sediment discharges, into two subsectors; the Amazon Macrotidal Mangrove Coast (AMMC) has a tropical humid climate with high

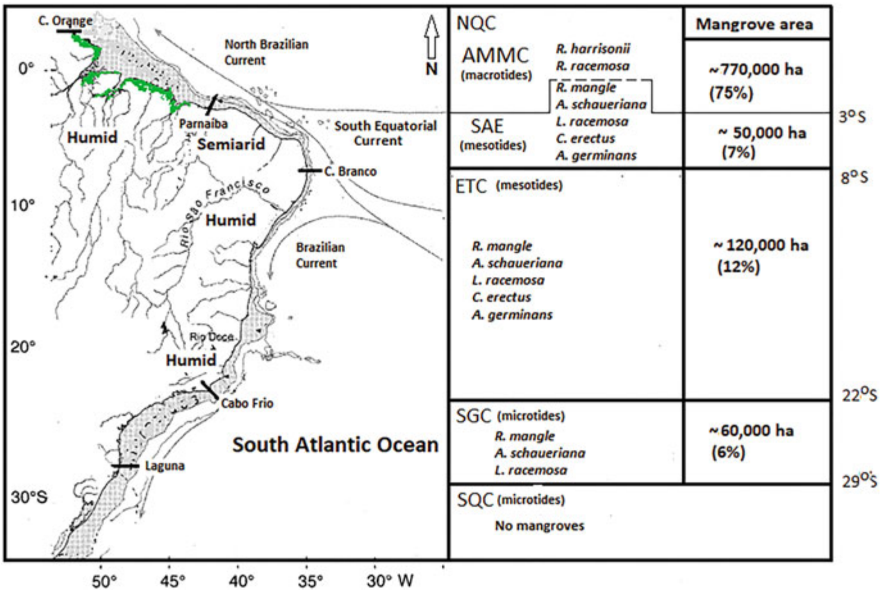

Fig. 20.1 Location of the major sectors harbouring mangrove forests along the Brazilian coast and their geographical setting, true mangrove species composition and approximate absolute extension and relative contribution of total mangrove area in Brazil

average temperature (~27 °C) year-round. This sector stretches from Cape Orange at 4.4°N to Parnaíba at 2.9°S and is dominated by a mud flat coast covered by mangroves, receiving an enormous contribution of fresh water (135,000 $m^3\ s^{-1}$) and terrigenous sediments from the Amazon Basin and under macrotidal (>7 m high) regime. This sector harbours about 75% of mangroves in Brazil and includes the largest (about 700,000 ha) continuous high-density mangrove forest in the world (Kjerfve and Lacerda 1993; Diniz et al. 2019). The second subdivision of the North Quaternary coast is the Semiarid Equatorial Coast (SAE), from Parnaíba to Cabo Branco at 7.1°S, under hot (~26 °C), semiarid climate. This subsector receives limited continental runoff (~2000 $m^3\ s^{-1}$), mostly from non-perennial rivers, with extensive mobile dune fields (Maia et al. 2006). Mangroves in this sector correspond to about 7% of the total mangrove area in Brazil scattered along estuaries, river deltas, bays, and coastal lagoons.

The second major sector extends from Cabo Branco to Cabo Frio at 22.8°S, called the Eastern Tertiary Coast (ETC). The littoral is characterized by the Barreiras Formation, a large tertiary deposit reaching the coast, forming cliffs throughout the littoral. This sector, mostly under a tropical rainy climate, harbours large mangrove forests occurring along the inner reaches of large bays and estuaries of medium-size rivers (total continental runoff of about 7000 $m^3\ s^{-1}$ and comprises about 12% of the total Brazilian mangrove area (Ekau and Knoppers 1999).

The last stretch of the Brazilian coast harbouring mangroves is the South Granitic Coast (SGC), extending from Cabo Frio to Laguna at 28.5°S. This coast presents a warm subtropical to temperate climate and constitutes the southern limit of mangrove in the South Atlantic Ocean. This is also the most urbanized sector of the Brazilian coast concentrating nearly half of the country's population in large, densely populated metropolitan areas, not infrequently housing mangroves. It contributes with 6% of the total Brazilian mangrove area (Lacerda et al. 1993; Knoppers et al. 1999; Ekau and Knoppers 1999) and comprises the most threatening mangrove forest in Brazil.

Brazil has the third largest extension of mangroves in the world, after Indonesia and Australia. The first national mangrove survey (Herz 1991) was based on airborne real aperture radar images collected from 1972 to 1975, giving a total approximate area of 1,380,000 ha. Based on 1980 area estimates, published by the different coastal states harbouring mangroves, Kjerfve and Lacerda (1993) reached a similar estimate (1,376,000 ha). These figures were considered overestimated by later authors, mostly due to the mapping techniques and uncertainty of local estimates. In 2010, national-scale mangrove maps, based on 2009 Landsat-5 data, reported Brazilian mangroves to cover an area of 1,114,300 ha (Magris and Barreto 2021). Onward, estimates of total mangrove area in Brazil vary by 30%. Global-scale mangrove maps published in the last two decades estimated Brazil's mangrove area to be 962,550 ha (Giri et al. 2011) and 1,012,300 ha (FAO 2007; Spalding et al. 2010). More recently, the Brazilian Environmental Ministry released the Brazilian Mangrove Atlas, based on 2013 Landsat-8 data, which estimated the national mangrove area to be near 1,398,900 ha (ICMBio 2018), whereas a consistent mapping by Bunting et al. (2018) suggested 1,107,200 ha, as a more reliable value based on detailed methodology and recent databases.

Most current literature lacks long time series of data to allow an exhaustive and systematic understanding of Brazilian mangrove coverage dynamics. Aide et al. (2013) published a detailed decadal (2000–2010) variation estimate of deforestation and reforestation in biomes in Latin America and the Caribbean. They showed mangroves in Brazil to have lost 28,200 ha and gained 38,900 ha during this period. In a recent survey (Diniz et al. 2019), based on a Google Earth Engine (GEE)-managed pipeline to compute the extension of Brazilian mangroves, on an annual basis, from 1985 to 2018, reached a similar conclusion. These latter authors also suggested little variability in mangrove area, with a percentage difference between 1985 and 2018 of about 2% (20,000 ha). Periods of expansion observed in the North Quaternary coast were followed by contraction in the East and South sectors. They reported an average total area for mangroves in Brazil varying from 974,000 to 1,012,000 ha. These values point a total area of Brazilian mangroves of ~one million hectares.

20.1.2 Forest Typology

Environmental setting, mostly climate and geomorphology, controls mangrove distribution, ecology, and biogeochemistry. These abiotic factors result in a typology of mangrove forests that are a key component to infer ecological characteristics and response (resistance and resilience) to environmental impacts. Typical mangrove forest types have been recognized by many authors. In Brazil, one of the first syntheses (Schaeffer-Novelli and Cintron-Molero 1990, 1999) applied a modified classification, firstly proposed by Lugo and Snedaker (1974), to Brazilian mangroves. Of the original six types proposed by these authors, Fringe, Riverine, Basin, Overwash, Dwarf, and Hammock forests, the last three types are specific cases of the first types. For example, high-salinity areas within mangrove stands can produce 'dwarf' types. Similarly, large coastal plains may display hammocks and overwash forests depending on micro-topography.

In this chapter, we use a recent proposed typology (Worthington et al. 2020): **Deltaic:** Shoreline fan-shaped alluvial plain derived from large fluvial runoff and river continental sediment. **Estuarine**: Funnel-shaped main channel with bidirectional tidal flows, characterized by large catchment area and high annual rainfall in most of the coast. The SAE sector shows low rainfall. **Lagoonal**: Shallow coastal waterbody, intermittently separated from the ocean by sand spits of dune field and usually formed parallel to the shore. Sediments vary from siliciclastic to bioclastic. **Open coast low energy:** Mud flats along the AMMC and **Open coast high energy:** Narrow mud flats in sheltered embayment's such as drowned bedrock valleys at the ETC. These have been adapted to the Brazilian Coast (Table 20.1). This seems sufficient to understand major ecological aspects related to typology and overlap

Table 20.1 A simplified distribution of mangrove forest types along the Brazilian coast

Sector	Sediment origin	Geomorphology	Major examples
AMMC	Terrigenous	Open Coast mud flats (low energy)	Pará State coast
		Deltaic	Parnaíba River Delta, Piauí State
		Estuarine	Anil River, Maranhão State
SAE	Terrigenous, spots on carbonates and bioclastic sands	Estuarine (low river input)	Jaguaribe River, Ceará State
		Lagoonal	Lagoa Guaraíras, Rio Grande do Norte State
ETC	Terrigenous	Estuarine	Jequitinhonha River, Bahia State
		Lagoonal (with bioclastic sediments)	Mundaú Lagoon, Alagoas State
		Open Coast (high energy)	Cumamú and Todos os Santos Bay, Bahia State
SGC	Terrigenous	Estuarine	Ribeira River, São Paulo State
		Lagoonal	Tijuca Lagoon, Rio de Janeiro State
		Open Coast (high energy)	Sepetiba Bay, Rio de Janeiro State

Definitions adapted to the Brazilian coast by the authors, based on the original definitions in Worthington et al. (2020)

with the three major types by Lugo and Snedaker (1974), fringe, basin, and riverine present along all different sectors of the Brazilian coast.

Riverine, or estuarine forests (Fig. 20.2.), the most abundant mangrove forest type, typically contain dense, tall straight-trunked trees along rivers and creeks and are flooded daily by tides. Their extension upriver depends on tidal amplitude and coastal geomorphology. In macro-tidal flat coasts with high river input, such as in the AMMC, this mangrove forest type reaches their maximum development occurring up to 40–60 km inland. In the SAE, these forests also migrate landward following the extensive saline intrusion resulting from low annual rainfall yet maximized by river damming. However, different from the AMMC, these forests are characterized by small trees scattered along depositional sedimentary areas along riverbanks.

The dominance of true mangroves (species that occurs solely or preferentially) in the mangrove habitat varies according to the magnitude of the fluvial flow vis-à-vis the tidal prism, such as in the Amazon and Orinoco river estuaries, riverine mangrove forests may diminish or even disappear in the strong competition with freshwater macrophytes. The permanent surface water flow velocity hampers the redistribution of ground litter, and the generally high productivity rates in these forests depends on fluvial nutrient inputs.

Fig. 20.2 Tall *Rhizophora mangle* trees of a typical estuarine stand at the Parnaíba River Delta in northeastern Brazil in the transition zone between AMMC and SAE. These forests attain extremely high biomass and carbon stock. (Photo from L. D. Lacerda personal archives)

Soils vary from oxic to suboxic, and organic matter respiration shifts from full aerobic to different suboxic metabolisms, with iron oxide and sulphate reduction as the major pathways. This has important environmental impacts in the response of mangroves to pollution (Lacerda 1998). A significant fraction of this primary productivity is exported to the ocean predominantly as particulate matter (Jennerjahn and Ittekkot 2002; Rezende et al. 2007).

In the SAE, however, the transport of mangrove materials varies according to season. During the relatively long dry season, mangrove litter accumulates inside the forest and creeks, and organic matter is broken and mineralized and exported as dissolved or soluble complexes and accumulates in estuaries, rather than exporting to the continental shelf. In the rainy season, materials are exported directly to the continental shelf. Figure 20.3 summarizes material transfer from riverine/estuarine mangroves to the continental shelf.

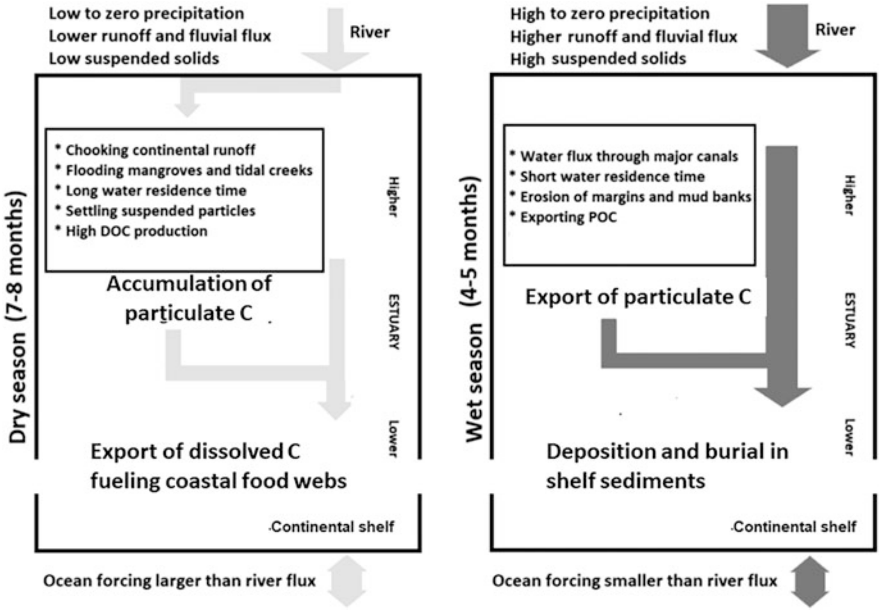

Fig. 20.3 Hydrodynamics and major carbon fluxes in mangroves of the North Quaternary Coast of Brazil. Dry season conditions are restricted to SAE mangroves. (Adapted from Lacerda et al. (2020))

Seasonal shifts observed in fringe and estuarine forests associated with fluvial flux variability affect biogeochemical processes at the soil–air interface. Theses shifts are particularly intense in the SAE, where even the precipitation of carbonates may occur, with contents varying from 4% to 11% in SAE mangroves (Albuquerque et al. 2014). Redox-sensitive micronutrients, such as Fe and Mn, are particularly affected (Lacerda et al. 1991, 1999; Aragon and Miguens 2001). Changes in Fe dynamics can directly affect P balance and availability of plant uptake as well as export to adjacent coastal areas (Silva et al. 1998; Marins et al. 2020).

Fringe forests occur along the borders of protected shorelines and islands and are periodically flooded by tides and display well-developed root systems. Due to their greater exposure to waves and tides, they are particularly sensitive to erosion and marine debris contamination, in particular macro-plastics and oil. They are also significantly impacted by changes in sea level (Jennerjahn et al. 2017; Ward and Lacerda 2021). Nutrient cycling and litterfall dynamics are highly dependent on hydrology and episodic climatic events rather than on the ecophysiology of the forest itself. Variable and important amounts of nutrients and carbon of marine origin participate in the nutrient cycling processes of these forests (Lacerda et al. 1988; Ovalle et al. 1990; Rezende et al. 1990; Silva et al. 1991).

Fringe forests frequently display broad extensions of salt flats at the terrestrial interface, when occurring along the quaternary plains in the northeast and eastern coasts. In the semiarid NE of Brazil, where sandy soils or dune fronts reach the fringe

Fig. 20.4 A basin mangrove forest in Southeastern Brazil, high tree density (4510 trees ha^{-1}), low tree height (6.1 m), and restricted tidally driven hydrology results in large sedimentation and creation of soil anoxic conditions. (Photo from L. D. Lacerda personal archives)

of the mangrove stand, *C. erectus* is predominant, as well as the occurrence of local sand dune species. The presence of *C. erectus* and species such as *Byrsonima* spp. and *Dalbergia ecastaphyllum* is an indicator of dune encroachment (Silva et al. 2020). Along the Southeastern coast, fringe forests occur mainly in the inner reaches of bays extending to the base of the Serra do Mar granitic escarpment where they sometimes mix with tropical rain forests. The mangrove canopy is regularly invaded by terrestrial plants, mostly epiphytes of Bromeliaceae and Orchidaceae families, and visited by terrestrial mammals typical of the Brazilian Atlantic Tropical Rain Forest, mostly monkeys, racoons, and small felines.

Basin forests (Fig. 20.4) grow inland in drainage depressions channelling terrestrial runoff towards the coast through tidal creeks. Water flow velocities are slow, and extensive areas of low topography are flooded. They are particularly sensitive to inundation, developing highly anoxic sulfidic soils. Under such redox conditions, calcophilous metals (e.g., Cu, Zn, Pb Cd), as sulphides, and particulate organic carbon accumulate and are efficiently preserved in soil (Silva et al. 1990; Lacerda 1998). The long residence time of waters within basin forests may also cause hypersaline conditions during low rainfall periods, in mangrove soil porewaters to a point that low topography areas may support only stunted trees or bare soils. These hypersaline areas are frequently colonized by obligatory halophytes from the Aizoaceae and Amaranthaceae families, and the export of mangrove litter fall to coastal areas is minimal. Carbon is mostly exported in dissolved form (Jennerjahn and Ittekkot 2002).

Within a given site, various studies have observed significant differences between fringe mangroves relative to landward or basin forests. Santos et al. (2017) reported average tree height of 10.1 m and 5.0 m and belowground biomass of 141 MgC ha^{-1} and 86 MgC ha^{-1}, in fringe and basin stands, respectively, in a mangrove in forests Sepetiba Bay, at the SGC. Similarly, Rovai et al. (2021), reported tree height of 5.6 m and DBH (diameter at breast height) of 6.6 cm in fringe stands relative to 5.6 m and 4.6 cm DBH in basin stands in Cananéia, also in the SGC.

20.2 Floral Biodiversity

20.2.1 Biogeography and Present Composition and Distribution of 'True' Mangroves

Plants acquired the 'mangrove habitat' during the Late Cretaceous (as early as around 86 million years ago) when *Nypa* and *Acrostichum* pollen and fruits were present in the Indo-West Pacific fossil record. These genera, however, only later appeared in the Paleocene in Brazil, but both disappeared from the fossil record thereafter. Later records of *Rhizophora* and *Pelliciera* in the Eocene (50–55 Mya) and *Avicennia* in the Miocene suggest the maximum dispersal between the Indo-West Pacific and Atlantic regions during the Cretaceous and Early Paleogene through the Tethys Sea via the Mediterranean region, which joined the Indian Ocean to the developing Atlantic Ocean. This model agrees with accepted paleoceanographic circulation (Haq 1984) and considers a unique centre of origin followed by radiate dispersal. Alternative routes through the Pacific Ocean are still unconfirmed by the fossil record (Srivastava and Prasad 2019).

Eocene mangroves *Acrostichum* and *Pelliciera* and the now extinct *Nypa* and *Brevitricolpites* gave way to Post-Eocene species, *Rhizophora*, the associate *Acrostichum*, and a remnant of *Pelliciera*, this latter genus disappeared from Brazil and remains exceedingly rare in the Caribbean region. From the Oligocene to present, no further extinction of Neotropical mangrove species occurred. Present mangrove species, apart from *Rhizophora* and *Avicennia*, reached the Atlantic western coast much later, during the Pliocene and Quaternary, when most contemporary species incorporated into the Brazilian mangrove flora (Rull 1998). During the Late Quaternary, two major sea level rise events occurred. The first in the last Pleistocene interglacial stage, about 123,000 years B.P., with a relative sea level from 2 to 8 m above present day. The second in the Holocene, about 5100 years B.P., with sea level about 5 m above present day. Landward migrations of the various facies zones paralleling the Brazilian coast occurred, including the erosion of forests, followed by a landward invasion of mangroves following saline intrusion (Hoorn 2006; Rodrigues and Senna 2011), as a response to changing sea level. Thus, the

Table 20.2 Updated list of species of 'true mangrove' trees and ubiquitous associated tree species in Brazil and their southern distribution limits

Family	Species	Southern limit
True mangroves		
Arecaceae	*Nypa* sp.	(Only in the fossil record)
Avicenniaceae	*Avicennia germinans* L. *A. schaueriana* Stapf. & Leech.	Atafona, 21°37′ Laguna, 28°30′
Combretaceae	*Conocarpus erectus* L. *Laguncularia racemosa* (L.) Gaertn.	Cabo Frio, 22°55′ Laguna, 28°30′
Pelliceriaceae	*Pelliciera rhizophorae* Pl. & Tr.	(Only in the fossil record)
Rhizophoraceae	*Rhizophora mangle* L. *R. racemosa* G. Meyer *R. harrisonii* Leechman)	Praia do Sonho, 27°53′ Parnaíba Delta, 2°46′ Parnaíba Delta, 2°46′
Malvaceae	*Hibiscus pernambucensis* Arruda	Juréia, 24°64′
Pteridaceae	*Acrostichum aureum* L.	Praia do Sonho, 27°53′

Ubiquitous associated species frequently occur throughout the coast, but abundance is very site-specific (sources: Dolianiti 1955; Breteler 1969; Hueck 1972; Prance et al. 1975; Araújo and Maciel 1979; Santos 1986; Cintrón-Molero and Schaeffer-Novelli 1992; Schmidt et al. 2013; Francisco et al. 2018)

present distribution and composition of mangrove forests along the Brazilian coast is a result of these recent sea level changes (Lacerda 2002).

Table 20.2 lists the extinct and living true mangrove species, those only found within the mangrove habitat throughout the coast of Brazil. True mangroves include three species of the family Rhizophoraceae, two of Avicenniaceae, and two of the family Combretaceae. In addition, it includes two other tree species which ubiquitously occur along with mangroves in Brazil, the Malvaceae, *Hibiscus pernabucensis*, and the Pteridaceae, *Acrostichum aureum*.

There is a complex of hybridization and introgression processes observed among *Rhizophora* species. Genetic diversities of the *R. racemosa* and *R. harrisonii* show little variability. *R. harrisonii* is already considered a hybrid of the other two species (*R. mangle* and *R. racemosa*). The two species are restricted to the AMMC. In contrast, *R. mangle*, with a regionwide distribution, presents large genetic differences between specimens sampled in the NQC and the southern regions of Brazil (Mori et al. 2015), in agreement with previous genetic diversity observed in the *Rhizophora* genus (Pil et al. 2011). Individuals from the northern populations of *Rhizophora* are more variable than those from southern localities. The two species of *Avicennia, A. germinans* and *A. schaueriana*, as well as of populations of *Hibiscus pernambucensis* showed a similar variability of the genetic signature (Takayama et al. 2013; Mori et al. 2010), when considering the entire geographical distribution along the Brazilian coast.

The branching of the South Equatorial Current (SEC) results in two different currents: a low-velocity, south-southwestward one, the Brazil Current (BC), and the high-velocity, north-northeastward North Brazil Current (NBC). This bifurcation allows a better transport of propagules from southern populations to the northeast and north regions, in particular the long-lived propagules of *Rhizophora*, but hampers the southward movement of northern populations propagules to southern latitudes (Pil et al. 2011; Mori et al. 2015).

20.2.2 Other Associated Plant Species

Approximately 112 plant species have been recorded associated with Brazilian mangroves. The majority, however, occur under quite specific situations and are not frequently present in association with mangroves. Others are ubiquitous, although not restricted to the mangrove habitat. Higher diversity of associated plant species occur at the interface between mangrove stands and the adjacent aquatic and terrestrial environments.

At the mangrove–land interface, degraded mangroves, and on recent sedimentation areas (estuarine beaches and islands), a high diversity of halophytic and salt-tolerant herbaceous plants establishes. The composition of this vegetation varies widely depending on soil type, hydrology, and climate. Some, like species of the Xyridaceae, Cyperaceae, and Potenderiaceae families, occur during relatively short periods when salt flats within basin mangrove forests are inundated during extreme rainy period. The most conspicuous species, however, are salt-tolerant graminoids and herbs (Fig. 20.5).

The most common are from the Amaranthaceae (*Salicornia gaudichaudiana* Moq., *Blutaparon portulacoides*); the Aizoaceae (*Sesuvium portulacastrum* L.); and the Bataceae (*Batis maritima* L.). Ubiquitous graminoid species (Poaceae) are *Sporobolus virginicus* L., *Paspalum vaginatum*, *Panicum* spp.; *Spartina alterniflora* Loisel, and the Cymodoceaceae *Halodule wrightii* Achers, which frequently colonize flats at the sea-edge of mangroves. The sea grass *H. wrightii* is the preferred fodder for manatees, which find shelter in mangrove tidal creeks of the AMMC and the SAE.

Under drier conditions, where sands frequently invade mangroves, or growing on quaternary sand ridges within mangroves, typical dry coastal ecosystems plants of the Brazilian coast are frequent; in particular, from the Fabaceae (*Dalbergia ecastophyllum* L., *Crotalaria retusa* (Forssk.) 'Schrank', *Desmodium triflorum* (L.) DC.); Convolvulaceae (*Ipomoea* spp.); Acanthaceae (*Ruellia paniculata* L.) families.

In the AMMC, freshwater macrophytes frequently invade the higher reaches of estuarine mangrove forests. Many typical Amazon species from flooded forests, such as the aquatic macrophytes of Araceae, *Montrichardia linifera* Arruda (Schott), Pontederiaceae *Eichhornia* spp., and palms (Arecaceae) *Euterpes oleracea* and Fabaceae *Pterocarpus officinalis* Jacq. abound, mixed with mangroves at the higher estuary (Calzavara 1972; Lacerda 2009).

In the SGC, where the Serra do Mar Mountain ridge extends along the entire length of this sector of the Brazilian coast, epiphytes from the Atlantic Tropical Forests invade the mangrove canopy, mainly orchids from the genera *Maxillaria, Epidendrum*, and *Brassalova* and bromeliads mostly of the genera *Tillandsia*,

Fig. 20.5 Dwarf mangroves in hypersaline areas which are natural components in many mangroves, particularly under semiarid climates but may also result from the presence of natural barriers (e.g., sand ridges), and changing hydrology due to road or pond construction close to aquaculture sites. Note grasses and herbs bordering the mangrove stand. (Photo from A. C. Ferreira personal archives)

Neoregelia, Vrieseia, and *Aechemea*. This ‘invasion’ results in many poorly understood interactions between mangrove and rainforest animals with these plant species. There are observations on Sesarmid (Grapsoidea) crabs (*Armases angustipes*) living in tanks of *Aechemea* and Neoregelia, also in the ETC (Abele 1972; Melo 1996).

Benthic seaweeds found in mangroves in Brazil include over 80 species, mostly from the Rhodophyceae. Diversity is higher in the high transparent waters of the SAE and the ETC and lower in riverine mangroves receiving large continental runoff contribution, like those of the AMMC. About 50% of species that have been recorded growing on roots and trunks, the remaining, not ubiquitous mangrove species colonize rocks, stones, and shell fragments (about 30%) or directly grow on sand or mud substrates (about 20%) (Oliveira-Filho 1984; Lacerda 2009).

As for the true mangrove tree species, some of these macroalgae (~20%) are also considered ‘true’ mangrove algae species and occur along all the different coast sectors including mangroves in Brazil. Cutrim (1998) observed 19 species in the mangroves of the São Luiz Island, in the AMMC. In the Cardoso Island, in the SGC, Yokoya et al. (1999) observed 18 macroalgae species colonizing mangrove trees, whereas in the same region, Sena et al. (2012) reported 13 species. These ‘true’ mangrove algae form ubiquitous associations, like those described elsewhere along the Western Atlantic; the Bostrichietum, typically colonizing trunks and roots, which is formed by a dozen Rhodophyceae including the genera *Bostrychia*, *Caloglossa*, and *Catenella*. The Rhizoclonietum, formed by over 10 species of the Chlorophyceae, mostly from the genera *Rhizoclonium*, *Enteromorpha*, and *Cladophora*.

In the SAE, where macroalgae attain higher diversity, the large foliage macroalgae *Gracilaria domingensis* (Kützing) Sonder ex Dickie and *G. cuneata* Areschoug play an important role in hypersaline mangroves on the SAEC, hosting numerous invertebrates, mostly molluscs. In this sector, a strong seasonal hydrological period promotes shifts in the dominance of local macroalgae species (Queiroz and Dias 2014).

20.3 Faunal Diversity

The Brazilian mangrove ecosystems also support an extensive and abundant variety of animals with approximately 600 species. Among these, the majority are fish, about 230 species, 131 crustaceans, about 50 species of molluscs, 86 birds, 27 mammals, mostly bats, 29 of other associated macrobenthic species, e.g., cnidarians, and 5 species of reptiles and an abundant, but poorly studied, insect fauna. Among these, some are rare and endangered species; others have significant economic importance, both commercially and to traditional human populations inhabiting mangrove adjacent areas.

Over 230 species of fish have been associated with mangroves in Brazil, with varied life strategies. Some resident species live, reproduce, and feed within mangrove habitats. These fish, in general small and abundant, are mostly micro/macro-consumers, herbivores or omnivores, and include cyprinodonts, eleotrids, poeciliids, rivulins, and gobiids. They show eco-physiological abilities that allow them to survive the extreme physical-chemical conditions of mangrove habitats, such as water cover and salinity variations, high temperatures, low dissolved oxygen, and high sulphide levels (Lewis III and Gilmore 2007). Others are transient species, spending juvenile stages within the forest tidal creeks for protection, or foraging in creeks and mangrove forest during high tide. These include omnivorous consumers like clupeids, mugilids, gerreids and sparids, and also centropomids, elopids, megalopids, and lutjanids, which are estuarine predators as adults (Chagas et al. 2006; Lewis III and Gilmore 2007; Osório et al. 2011). Many mangrove fish species are of economic importance but have been overfished, and some are presently threatened in many sectors of the coast; among them *Lutjanus analis, Macrodon ancylodon, Mugil liza, M. platanus, Negaprion brevirostris, Ocyurus chrysurus, Pomatomus saltatrix, Pristis pectinate, P. perotteti, Rhinobatus horkellii, Sardinella brasiliensis*, *and Umbrina canosai* (MMA 1999).

Many genera of Decapod Crustaceans are present in mangroves. Fossorial fiddler crabs (Ocypodoidea) comprising 12 species, including the endemic to the ETC, *Minuca victoriana*, often promote high bioturbation of the sediments, due to high density of the populations and detritivore/microherbivore feeding, an effect similar to high-sized *Ucides cordatus*. Grapsoid crabs are also abundant in mangroves and are more generalists, foraging on detritus, leaves, bark, propagules, algae, or small invertebrates, including crabs (Lacerda 1981; Lee 1998). Some Grapsoids (*Goniopsis cruentata*, *Sesarma rectum*) seem to influence forest composition, and consequently their structure, architecture, and biomass, through propagule selective feeding (Smith et al. 2019; Ferreira et al. 2019). Of notice is the tree climbing Grapsoid *Aratus pisonii* that spends all its adult life foraging in the mangrove canopy, feeding on bark, leaves, and algae (Lacerda 1981). Other crabs are of large economic significance, but have been overexploited, such as *Ucides cordatus, Cardisoma guanhumi*, and *Callinectes* spp. (*C. sapidus*, *C. danae, C. exasperatus, C. bocourti,* among others) and the shrimps *Macrobrachium heterochirus, Merguia rhizophorae, Farfantepenaeus brasiliensis, F. paulensis, Penaeus notialis,* and *Litopenaeus schmitti* (MMA 1999).

There is a total of 56 species in 29 families of molluscs, mostly bivalves of economic importance, including clams, *Anomalocardia brasiliana*, *Lucina* sp., *Tagelus gibbus*, and *T. plebeius*; oysters, *Crassostrea brasiliana* and *C. rhizophorae*; and mussels *Mytella falcata* and *M. guyanensis*. Wood boring *Teredo* spp. are reared in mangroves of the AMMC by felling tree trunks and leaving them on the sediment surface to be colonized by the mollusc. Apart from those species of economic importance, a diversified fauna of micromolluscs dominate in the algal microhabitat, mostly from the Columbellidae, Neritidae, and Pyramidellidae (Queiroz and Dias 2014).

Brazilian mangroves have a highly diversified avifauna, of over 86 species, including colonies of the iconic scarlet ibis *Eudocimus ruber*, and the endemic, yellow-crowned night-heron (*Nyctanassa violacea cayennensis).* Mangrove ecosystems of Brazil also serve as a resting and feeding habits for several neotropical and high-latitude migratory birds, including the yellow socoí (*Ixobrychus involucris*), the purple-billed buck (*Oxyura dominica*), and *Gelochelidon nilotica* (MMA 1999).

Mammal species are not compulsory inhabitants of mangroves in Brazil. Large species require extensive territories, and therefore, the extensive continuous mangrove fringe of the AMMC present the highest mammal diversity among the coastal sectors. Bats are the most abundant mammal order. The family Phyllostomidae is particularly diversified. In a mangrove stand in the SAE, Soares et al. (2011) reported 10 genera and 11 species from this family, most frequent were *Artibeus lituratus*, *A. planirostris*, *Platyrrhinus lineatus*, and *Sturnira liliumabout* corresponding to 78% of the total bat individuals (80) collected in the area, other families are Emballonuridae, Noctilionidae, and Vespertilionidae. Similar results were observed in the AMMC (Cruz et al. 2007), but bat diversity is still poorly studied in mangroves of Brazil.

Small racoons and marsupials are also frequent inhabitants of the mangrove canopy. The crab-eating racoon *Procyon cancrivorus* (Canidae) is ubiquitous in mangroves along the entire Brazilian coast, whereas marsupials from the Didelphidae: *Didelphis marsupialis* L., *Philander opossum* L., and *Micoureus demerarae* (Thomas) forage insects in the canopy where mangroves occur adjacent to terrestrial forests, as in the AMMC and the SGC (Andrade and Fernandes 2005). Among the Primates, Cebiae is the most abundant and includes the red-handed howler monkey 'Guariba' (*Alouatta belzebul ululante*), which can be considered a permanent resident of AMMC mangroves, *Chiropotes satanas, Saimiris sciureus, Cebus capucinus,* and *C. apellata*. All forage in the canopy and on crustaceans and molluscs in the exposed low-tide muddy soil (Fernandes 2000). Threatened species, in addition to the monkey *A. belzebul,* are the manatee (*Trichechus manatus*) and reptiles (e.g., *Cayman latirostris*).

20.4 Phytoplankton, Zooplankton, and Microbial Diversity

The microbiota community of mangroves in Brazil is still poorly known, which hinders the recognition of endemic species or distribution patterns among the coastal sectors. In general, the microbiota is constituted by a high diversity of diatoms, dominated by *Auliscus coelatus, Actinopthycus undulatus, Biddulphia* sp., *Cocconeis scutellum, Cyclotella stylorum*, *Fragilaria* sp., *F. nummuloides, Navicula lanceolata,* and *Thalassionema* spp. (Fig. 20.61A, 1B) (Pires and Lacerda 2004). These influence the biogeochemical processes at the sediment–water interface of the mangrove forests, where they constitute biofilms with fungi and bacteria, which

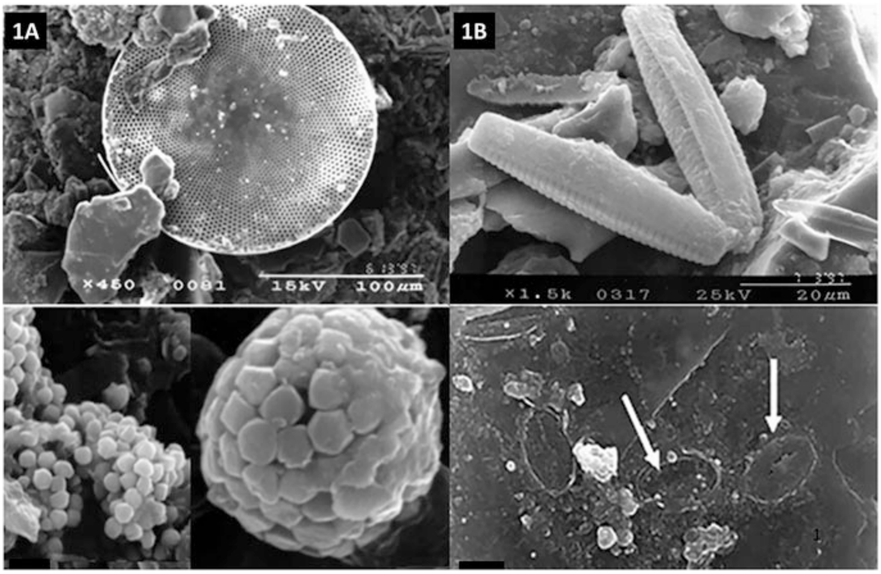

Fig. 20.6 Microbiota (1A and 1B) (diatoms) and bio-mineralization in mangroves sediments from Brazil (Pires and Lacerda 2004, 2008, 2015). Left-hand lower (1C): Pyrite crystals and framboidal aggregate; Right-hand lower (1D): impression marks of microorganisms where they were attached to crystals facilitating weathering. (Photo courtesy of L. C. Pires)

promote the rapid formation of bio-mineralized minerals, such as framboidal pyrites which play a key role in nutrient and trace element geochemistry in mangrove sediments (Fig. 20.61C) (Pires and Lacerda 2008). The biomineralization processes, mainly sulphate reduction and pyritization, are eventually responsible for the capacity of mangroves to immobilize pollutants, in particular trace metals of environmental significance, decreasing their bioavailability to mangrove plants and animals. Benthic microorganisms also facilitate the weathering of sediment grains (Fig. 20.61D) (Pires et al. 2015).

Of relevance is the presence of toxic microorganisms found in mangrove fauna, which may pose threats to human consumption. Among these, *Pseudo-nitzschia* spp., *Dinophysis acuminata, Prorocentrum minimum, Gymnodinium catenatum, Phaeocystis* spp., *Chattonella* spp., and *Heterosigma akashiwo* have been recorded in the mangrove mussel *Mytella guyanensis* in the SGC (Mafra et al. 2006).

Zooplankton species are those typical of neotropical estuaries, mostly Crustaceans, such the abundant Copepods *Acartia (Odontocartia) lilljeborgi, Temora turbinata*, *Pseudodiaptomus acutus*, *Paracalanus aculeatus, Parvocalanus crassirostris*, and ubiquitous larvae of Decapoda and Cirripedia. Also common are Appendicularians *(Oikopleura* spp*.)*, Chaetognaths (*Sagitta* spp.), and veliger larvae of molluscs and nematodes that migrate into mangrove creeks (Santos et al. 2009).

Marine fungi found in Brazilian mangroves are typical of higher fungi of warm waters. They infest submersed roots, stems and twigs, as well as sessile animals and algae. Over 60 species of marine fungi were recorded, but only a few seem to be host-specific. The distribution and species composition of the mycoflora vary according to submergence of the infested tree parts. Marine fungi overlap with terrestrial species at high tide level. Typical host-specific species of marine fungi observed in Brazilian mangroves are the Ascomycetes; *Didymosphaeria rhizophorae, Keissleriella bleparospora*; *Leptosphaeria australensis,* and *Phoma* sp. The Deuteromycetes includes *Cytospora* sp., on *R. mangle, Rhabdosphora avicenniae* on *A. germinans* (Kohlmeyer 1969).

Most terrestrial fungi occur as parasites of living leaves. Ubiquitous host-specific species on *R. mangle* are the Acomycetes *Anthostomella rhizophorae, Physalospora rhizophoraei,* and *P. rhizophoricola* (Batista et al. 1955; Vizioli 1923). Among the Deuteromycetes, the genera *Pestalotia* and *Cercospora* show the highest species diversity.

Marine fungi play a key role in litter decomposition processes and nutrient cycling. Deuteromycetes and Phycomycetes, in particular *Aspergillus* and *Penicillum*, are the dominant fungi involved in the litter decomposition process of mangrove organic matter (Barreto 1988).

In addition to the algae, about 60 species of fungi belonging to all groups found in warm waters infest submersed roots, stems, and twigs; only a few, however, are host specific. This group of organisms plays a central role in biomass decomposition and nutrient cycling within mangroves. Major species belong to the Calymperaceae and the Lejeuneaceae. Among the first, *Calympera palisotii* is the most conspicuous species and considered totally adapted to the mangrove habitat. *C. rigidula* and

Lejeunea laetevirens are also widespread, especially in mangroves under humid climate (Visnadi 2008).

20.5 Ecology and Ecological Processes

20.5.1 Major Aspects of Mangrove Tree Ecological Adaptations

The occupation of the intertidal habitat by mangroves required adaptations to the waterlogged conditions and tidal regime, mostly including well-known and repeatedly described features of the anatomy and histology of mangrove plant organs. Ubiquitous adaptations are (a) complex architecture of aerial roots, typical of the Rhizophoraceae, which gives physical support in a waterlogged and tidal environment, submitted to wave and current action, and often strong winds.

Aerial roots also promote sediment trapping and high sedimentations rates, in general several millimetres per year, which mitigate the impact of sea level fluctuations (Ellison and Stoddart 1991); (b) brackish to saline waters drive physiological adaptations which include excess salt exclusion at the root level, typical of the *Rhizophora*, salt excretion/secretion organs and mechanisms in leaves, typical of the *Avicennia*, and cuticular transpiration in *Laguncularia*; (c) wax covered and/or succulent leaves, enriched in tannins, contribute to diminishing water loss and protect from UV irradiation. Tannins also keep low insect herbivory by decreasing plant protein digestibility (Lacerda et al. 1986); (d) the abundant lenticels located on aerial structures close to the water level exchange gases directly with the atmosphere, whereas widespread distribution of the aerenchyma in stilt roots, knee roots, and pneumatophores facilitates oxygen transfer from the photosynthetic canopy to roots. Lenticels are also present on propagules of many mangrove species.

In addition to adaptations to cope with the stressful conditions of the intertidal zone, mangrove plants also adapt to redox conditions within the soft, muddy substrate, which are often sub-oxic or anoxic, caused by the rapid consumption of oxygen by bacterial activity and low downward flux of oxygen through the fine-grained sediment. Roots of mangrove plants exude oxygen in the soil creating oxidized rhizospheres and precipitating iron plaques around the external cortex of roots (Fig. 20.7). Iron plaques are very efficient in impeding the uptake of soluble toxins present in the anoxic environment, including sulphide, metals, and microorganic pollutants (Lacerda 1998).

Viviparity, which is most developed in the species of Rhizophoraceae, but not exclusive of this family, produces seeds with cotyledons and the beginning of a plumule or embryo contained in the testa, but germination happens only after the testa or shell of the seed rots and ruptures on trees or on the substrate. Viviparity grants mangroves their pantropical distribution since they may still be viable after 6–10 months floating in seawater. A more recent role of viviparity is to allow easy

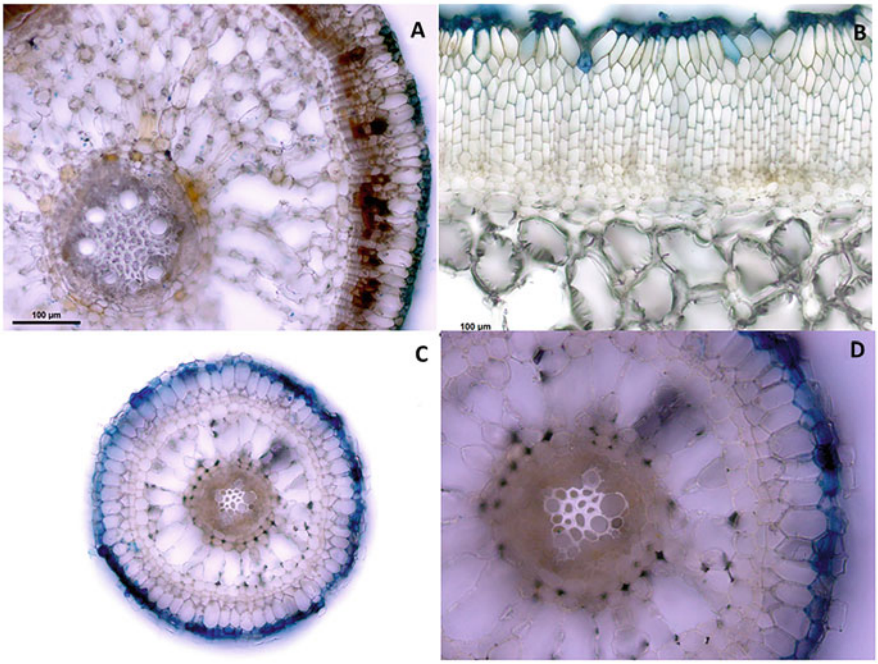

Fig. 20.7 Iron deposition (dark blue), forming iron plaques on the external surface of mangrove roots of *R. mangle* (**a**, **b**) and *A. germinans* (**c**, **d**). Details of the preferred accumulation site at the external epidermal cells of roots, which helps avoiding the uptake of toxic substances are shown in B and D. (Photos courtesy of I.K.C. Belmino)

migration of mangroves landward or poleward following global climate change, enhancing resilience of these ecosystems to the changing environment of the Anthropocene.

20.5.2 Biomass, Productivity, and Carbon Allocation

Biomass, productivity, and carbon allocation vary widely among Brazilian mangroves, dependent on latitude, climate, and geomorphology. Mangroves along the AMMC receive a large amount of rainfall and high nutrient inputs from the continent and thus present the largest forests, with aboveground biomass (AGB) varying from 290 to 451 Mg ha^{-1}; this results in C accumulation in living biomass varying from 125 to 196 MgC ha^{-1} (Santos et al. 2019). Kauffman et al. (2018a) reported similar AGB values in nine tall (17 to 29 m) forests along the Amazon influenced coast. Their study reported an average aboveground Carbon allocation of 159 MgC ha^{-1}, and the average dead wood on the substrate C mass was 14 MgC ha^{-1}. Total aboveground C stock was 31% of the ecosystem total C stock, the remaining 70%

were preserved in mangrove soils either as belowground root biomass (BGB) or organic detritus. The effect of climate is clear when comparing AMMC mangroves aboveground biomass with that of semiarid mangroves at the same latitude in NE Brazil (SAE), where aboveground C biomass reaches only 72 MgC ha^{-1}. In the AMMC total C stock (AGB + C in soil) varies from 362 to 746 MgC ha^{-1}, while mangroves in the semiarid NE present a maximum of 413 MgC ha^{-1}, mostly accumulated in soils (Kauffman et al. 2018b).

Total AGB and C accumulation is highest along the AMMC and decreases steadily as latitude increases. AGB of a highly developed *R. mangle* stand (15–20 m height) in the SAE region (Rio Grande do Norte state) reached a biomass of 99.25 ± 29.77 Mg ha^{-1} (43.67 ± 13.10 MgC ha^{-1}) (Ferreira et al. 2019). Within a *L. racemosa* dominated mangrove forest in Espírito Santo (ETC), about 20°S, with a typical tree height of southern stands (e.g., 2.7–7.7 m, mean 4.1 m), AGB and soil carbon values were 48.6 Mg ha^{-1} and 24.3 MgC ha^{-1}, respectively. Portillo et al. (2017) noted a positive relationship between AGB-C and soil humidity in the southern coast of Rio de Janeiro, about 23°S, a *R. mangle* fringe forest with average height of 6.1 m, displayed AGB-C of 30.6 MgC ha^{-1} and BGB of 7.5 MgC ha^{-1} (Silva et al. 1991). In the same region (Sepetiba Bay), Santos et al. (2017) estimated average BGB-C of 104 MgC ha^{-1}. This high variability, however, is probably due to different methodologies applied by the two studies, as well as different forest types. Rovai et al. (2021) published the most complete analysis of C sequestration in mangrove biomass in Brazil. They calculated C tock distribution in mangrove stands in the Cananéia region, a pristine area in São Paulo state at the SGC. As also observed in other studies, they observed higher AGB and C stock in fringe forests when compared with forests located further inland. The average C in the AGB was 52.7 MgC ha^{-1}, whereas in the BGB was 57.2 MgC ha^{-1}. Notwithstanding the relative low C stock in the biomass, soil carbon stock was 270 MgC ha^{-1}.

In summary, although C stocks have only been recently estimated for mangroves along the Brazilian coast, the existing estimates of ABG-C stock are higher in the AMCC (125–258 MgC ha^{-1}), where trees are typically taller (>15 m), when compared with the ABG-C stocks of the SGC (30–52 MgC ha^{-1}), which are typified by shorter tree heights (<7 m). Since annual rainfall is similar in the two regions, the difference is probably a response to lower average temperature (<25 °C) and winter extreme temperature (<10 °C) in the SGC relative to the year-round warmer temperature (>26 °C) in the AMMC. Within a given region, AGB and BGB can differ significantly, as a response to nutrient availability, particularly N:P molar ratios (Rovai et al. 2021), soil composition and granulometry (Madi et al. 2017), and rainfall (Kauffman et al. 2018a, b).

The distribution of AGB among plant tissues are relatively similar in all mangrove regions in Brazil, and variation is predominantly linked to species, although studies are relatively scarce. Leaf biomass contributes to about 6–10% of the total AGB, being relatively higher in *Avicennia* than in *Rhizophora* and *Laguncularia* (Medeiros and Sampaio 2008), whereas prop roots of *Rhizophora* can contribute up to 20% of the total AGB (Silva et al. 1991). Different methodologies to estimate AGB and BGB hamper a deep discussion on the allocation among different wood tissues. Even forests located in the same bay can have highly varied AGB:BGB ratios, as in Sepetiba Bay, where *Rhizophora* forest from different sites were reported to have AGB:BGB ratio varying from 0.1 to 3.9, depending on the methodology used (Silva et al. 1991; Santos et al. 2017).

Net aboveground primary productivity of mangroves is the sum of wood growth (NPP_{wg}) and total litterfall (NPP_{lf}). Many authors have studied litterfall in Brazilian mangroves, working mostly on mature forests, where wood growth has a lesser contribution, but this has seldom been monitored. Therefore, estimates of net primary productivity of mangroves in Brazil are probably underestimated. In the Cananeia region in the SGC, NPP_{wg} (464 gC m^{-2} $year^{-1}$) was higher than the NPP_{lf} (295–370 gC m^{-2} $year^{-1}$) (Rovai et al. 2021), suggesting that the underestimation could be of at least a factor of 1.4. This may be of particular importance when estimating the ecosystem's capacity for C sequestration and the ability of mangroves to mitigate CO_2 emissions. Immature forests, frequently associated with natural regeneration or active replanting projects, can also incorporate a large amount of C as wood growth.

Litterfall rates, the most reported parameter in productivity studies, like biomass estimates, are variable and are highly influenced by temperature and annual rainfall and species composition. Irrespective of these variables, leaves usually represented the largest fraction of the litterfall (50%–80%), twigs and small branches, followed by reproductive parts, which are highly variable depending on species phenology and climatology (Silva et al. 2007; Bernini and Rezende 2010). Season is an important variable, mostly in the SAE region and the higher latitudes of the SGC, where greater productivity occurs in the rainy season, as shown in several other mangroves worldwide (Bernini and Rezende 2010; Portela et al. 2020; Gomes et al. 2021). The highest productivity was recorded in areas of low salinity of the interstitial water, an available adequate supply of nutrients and high rainfall. In the AMMC, litterfall varied from 51 to 203 gC m^{-2} $year^{-1}$ (Fernandes 2003; Gonçalves et al. 2006; Nascimento et al. 2006; Fernandes et al. 2007; Mehlig 2001). Similarly, in the high rainfall coast of São Paulo, in the SGC, with large freshwater and nutrient supply, litterfall may reach 333 gC m^{-2} $year^{-1}$ (Rovai et al. 2021). Close to the southern limit of mangroves in Brazil, litterfall is somewhat lower (48 gC m^{-2} $year^{-1}$), in Paranagua Bay (Sessegolo 1997), and 174 gC m^{-2} $year^{-1}$ in Santa Catarina (Cunha et al. 2006). However, irrespective of latitude, local conditions seem to be the major driver influencing litterfall rates.

20.5.3 Nutrient Cycling

About half of the in situ mangrove productivity is exported to coastal areas as macrodetritus and particulate organic carbon (POC), the remaining being consumed by herbivores or buried in the mangrove soil. Sedimentary organic matter suffers partial decomposition in the mangrove environment and is exported as dissolved organic carbon (DOC) to pore waters and thence to tidal creeks. The sub-oxic to anoxic conditions prevailing in mangrove soils impede the total conversion of the deposited organic matter into energy. A larger portion of the produced organic matter falls to sediments as leaf litter and is buried and accumulated there for exceptionally long periods. The anaerobic decomposition of mangrove organic matter, mostly performed through dissimilatory sulphate reduction by anaerobic or facultative anaerobic sulphate-reducing bacteria, generates high concentrations of 'young', reactive DOC in pore waters, which are exported through tides to adjacent coastal waters. The conservativity and the C:N:P Redfield ratio are used to trace metabolic processes in the water mass and the origin(s) of the organic matter. However, the ration may vary under limiting micronutrient supply (e.g., Fe) (Ovalle et al. 1990; Rezende et al. 1990, 2007, 2020).

Sulphate reduction products may form authigenic minerals (Pyrite, Greigite), participate in oxyreduction reactions involving phosphorus and silica coprecipitation, or be incorporated by organisms. A proportion of these compounds plus mangrove-derived DOC are transferred to adjacent coastal systems where it can contribute to the cycling of nutrients in estuaries and is linked to productivity of commercial fisheries in most tropical areas. In areas where oceanographic conditions permit, mangrove DOC and sulphate reduction by-products can be exported to the continental shelf and slope, although its importance to the trophic ecology of these areas is virtually unknown along the Brazilian coast.

Mangroves act as exporters or importers of nutrients depending on site-specific conditions (Silva et al. 1998; Marins et al. 2020). In general, however, a net nutrient accumulation seems to be a characteristic property of mangroves. In many areas, nutrient inputs may be limiting, as in the SAE, but mangroves may attain high productivity rates by inducing an efficient recycling of limited nutrients (Marins et al. 2020). Sediment fauna also influences this process but also seems site-specific (Ferreira et al. 2019).

The response of mangroves as net sinks or sources of nutrients is a key parameter to proper coastal management, aiming to establish the support capacity of coastal areas to withstand excess nutrient inputs from anthropogenic sources. The exporter or importer nature of mangroves will depend on the ecosystem 'health' when the nutrient load is applied and the magnitude of the discharges. Removal efficiency of nutrients is dependent on the oxic conditions of surface and interstitial waters (Silva et al. 1998). Eutrophication, by reducing oxygen levels, reduces the efficiency of nutrient accumulation by mangroves (Marins et al. 2020). Also, the import/export nature of a given mangrove will depend on the specific response of functional groups of organisms to specific constituents (Ferreira et al. 2019). Therefore, the results obtained in mangroves ecosystems in Brazil limit to a large extent, the potential use of mangroves as a natural barrier to the nutrient transport to adjacent estuarine and coastal areas, and their role as natural filters to nutrient-enriched effluents.

20.6 Ecosystems Services

Among wetlands, mangrove forests are some of the most important, as a result of the high provision of goods (fisheries, timber and other products), and services (biodiversity conservation, fisheries breeding areas, coastal protection, carbon sequestering), in relation to their extent (Alongi 2002; McLeod and Salm 2006; Spalding et al. 2010; Barbier et al. 2011). Mangroves also indirectly deliver farther-reaching benefits, such as serving as habitat for terrestrial and marine species (Nagelkerken et al. 2008). At least 776 species of birds, fish, molluscs, arthropods, and plants are associated with these ecosystems in Brazil (Schaeffer-Novelli 1999), with even larger numbers in Indo-Pacific mangroves (Ricklefs and Latham 1993). In some developing countries, mangroves are estimated to contribute to national economies with US$ 33–57 thousand per hectare per year (e.g., Sathirathai and Barbier 2001).

In the context of climate change and its impacts, mangroves play a significant role in coastal protection and sequestering of greenhouse gases (GHG) (Alongi 2015; Ward et al. 2016). Mangroves are significant sinks of atmospheric carbon, storing several times more carbon than terrestrial forests. Indeed, mangroves account for around 3% of carbon sequestered by tropical forests, although represent around 1% of the forest area. This relatively significant contribution is not only due to high productivity rates, but to the large accumulation of carbon in anoxic sediments, protecting organic matter from oxidation and so contributing to mitigating climate change (Donato et al. 2011; Ray et al. 2011; Murdiyarso et al. 2012; Alongi 2014).

In Brazil, mangroves and all their subsystems, were, until recently, environmental protected areas (Schaeffer-Novelli et al. 2012; Ferreira and Lacerda 2016; Borges et al. 2017). Despite loosened-up regulations, direct use of mangrove products, as fuel wood, charcoals, and timber was prohibited, although local traditional populations can use these resources. Among fisheries products, mangrove crabs are the most valuable resource, but fisheries, in general, are poorly managed to preserve stocks and illegal fishing still occurs in most isolated areas. Mangroves support a significant, although not yet fully quantified, portion of coastal fisheries, through organic matter and nutrients fluxes and as a nursery for many marine and estuarine species. For example, it was estimated 1 hectare of preserved mangrove forest houses around 5.1 t of mangrove crab *Ucides cordatus* and yield around 20 t of animal biomass per year including fishes, molluscs, and crustaceans (IBAMA and CEPENE 1994; Rocha Junior 2011).

Mangroves are efficient biogeochemical barriers to the transfer of pollutants generated in coastal landfill sites to the sea, an effect verified by restored mangroves in Australia and Southeast Brazil (Clark et al. 1997; Lacerda et al. 2000). Indeed, mangroves can trap toxic metals (Fe, Mn, Zn) in the root–sediment interface, being able to colonize metal-rich sediments and hence having a great potential to reduce trace metal pollution, an extremely significant service in low-resource developing countries (Machado et al. 2002, 2004). Mangroves sequester other heavy metals (Hg, Cd, Cu) and other pollutants in their sediments, which can be released to estuarine/deltaic waters by human activities (sewage spilling, dredging, deforestation, alterations in river basins) and climatic driven causes (erosion, sea level rise) (Lacerda and Miguens 2011; Lacerda et al. 2021).

Mangroves act as natural protection for the shoreline in cases of erosion and flooding. They act as a filter for sediments and pollutants, while also playing an important role in carbon sequestration and storage. These services can mitigate and adapt the coastal zone to the effect of sea level rise. However, recent research highlights the widespread indirect impacts of human activities, such as aquaculture, which result in a reduction of ecosystem services, resistance, and resilience to environmental impacts (Lacerda et al. 2021).

Cultural and recreational services have already been identified to be often neglected in mangrove areas in Brazil (Queiroz et al. 2017; Borges 2019). Other services, such as serving as nursery areas and local climate regulation, are also rarely identified by local stakeholders in Brazil (Borges 2019) and seem to receive little attention by academic research. Some of the few examples are Aschenbrenner (2014), which focuses on fish species, and a short overview that includes a wider range of species by Souza et al. (2018).

However, recent research highlights the widespread of indirect impacts of human activities, like aquaculture, over forests, which result in a reduction of ecosystem services and in resistance and resilience to environmental impacts (Lacerda et al. 2021). Since most people prefer to see a forest instead a degraded area, the use of natural or reforested mangrove areas for contemplation, teaching, or small-scale tourism can contribute with awareness and preservation of the stands, being an additional service provided by mangroves (Ferreira and Lacerda 2016).

20.7 Livelihoods

Original as well as pre-historic inhabitants of Brazil traditionally used mangroves for many purposes, including food, wood, and energy sources. There is widespread archaeological evidence of mangrove utilization between 9000 and 3000 years B.P., which varied from site to site, depending on the characteristics of the human group and available natural resources. Early inhabitants formed semi-permanent settlements along mangrove coasts, where an abundant protein-rich diet consisted of molluscs and crustaceans, and also fish and birds, when available. They left large accumulations of shells, organic waste products, and cultural debris, referred to as *sambaquis*, which provide important information on these original populations, their food habits, and use of natural resources (Kneip and Pallestrini 1984; Scheel-Ybert et al. 2009). On the Amazon coast, for example, the proximity between areas of mangroves, beaches, saline fields, and tropical upland forests allowed a large concentration and diversity of resources for sedentary human populations who have settled there for at least 6000 years (Silveira and Schaan 2010).

During colonization by the Portuguese, native populations were driven to near extinction. The arriving Europeans initially considered mangroves a nuisance. During the whole period of the Portuguese occupation, even in areas shortly dominated by the Dutch, the more widely applied ‘management’ approach to mangroves was suppression and replacement by roads, buildings, or plantations in a context of urbanization efforts through land reclamation (Araújo da Silva 2011). But they quickly discovered the quality of mangrove timber for construction, mostly for poles and construction of boats, and later for tannin. By 1760, mangrove products were so valuable that resource management was required. D. Manuel Jose I, then King of Portugal and Brazil, issued the very first law to protect mangroves, determining penalties to people felling mangrove trees not previously debarked. This was a request from the past stockholders, in this case the leather merchant guild, who had largely used mangrove bark tannin, a piece of knowledge acquire during the Portuguese dominance in Asia (Vannucci 1999).

On 25 January 1812, Prince D. João VI of Portugal and Brazil founded the first Practical Chemistry Laboratory of Brazil in Rio de Janeiro, to study applications for the different local natural materials to decrease dependence on imported goods (Rheinboldt and Azevedo 1955). One of the first tasks of the Laboratory was to develop alternative processes to produce hard soap, aiming to decrease the expenses with importing soda (Lacerda and Santos 2004). Brazil at the time consumed imported low-quality soft soap in small barrels from São Tome and Principe Islands or expensive hard soap from England. The goal was to produce hard soap that could be transported and sold in bars. The first process, developed under the directorship the Brazilian Bachelor and Priest Francisco Vieira Goulart (1765–1839), involved the use of 50% NaOH-rich mangrove ashes and 50% common salt to produce good-quality hard soap. The process largely reduced soap prices. Mangrove ashes easily substituted the imported soda and had the advantage of being abundant and with an exceptionally low cost of production, obtained along the then extensive mangrove forests of Guanabara Bay (Schwartzman 1979), the same area previously protected following pressure from the leather guild.

Today, in north and northeast Brazil, mangrove wood is used to build houses and other structures, to obtain medicinal compounds and tannin, and to produce firewood and charcoal (Glaser 2003; Vasques et al. 2011; Loureiro and de Oliveira 2019). In southern Brazil, a region that is more economically developed than other regions, mangrove trees are also used, although such use had been declining until a few years ago (Santos and Lana 2017).

Mangrove fisheries contribute to food security all along the Brazilian coast. In north Brazil, for instance, near-shore bivalve, shrimp, and crab fisheries are vital to the livelihoods of local populations (Diele et al. 2010; de Carvalho and Jardim 2019). Crabs and other fisheries products are essential to the livelihoods of populations in northeastern Brazil (Araújo and Calado 2008; Guedes et al. 2018; Loureiro and de Oliveira 2019), as well as in the Southeast (de Oliveira Côrtes et al. 2014) and South regions (ICMBio 2018), including highly urbanized areas (Gillam and Charles 2019).

Despite numerous conservation efforts in place today, especially in the form of protected areas, and their importance for the livelihoods of vulnerable communities, mangroves continue to be degraded by urbanization and real estate speculation (Araújo da Silva 2011), including by marginalized groups that are being pushed to occupy mangrove areas (Gillam and Charles 2019; Loureiro and de Oliveira 2019). There are reports by local users of reduced availability of resources such as crabs due to increased pressure (Borges 2019; de Carvalho and Jardim 2019) and other environmental problems, e.g., mangrove pollution (de Carvalho and Jardim 2019).

20.8 Regeneration and Restoration of Mangroves

Mangrove clearing and fragmentation continue today, mainly in Southeast Asia, although a slight reduction in forest loss rates has been noted in the Americas, Africa, and Australia (Hamilton and Casey 2016; Friess et al. 2019). Recent research highlights the widespread indirect impacts, which result in a reduction of ecosystem services, and in resistance and resilience to environmental impacts (Lacerda et al. 2021). Brazil has around 9419 km^2 of protected mangrove areas, around 85% of their total mangrove area, but the level of protection does not impair deforestation, for example, by urban or infrastructure settling, or establishment of salt or aquaculture ponds (Ferreira and Lacerda 2016; Worthington and Spalding 2018). So, mangroves need to be effectively conserved and their regeneration protected, and eventually rehabilitated and restored.

Mangroves are relatively resilient communities that can recover after disturbances, depending on the frequency and magnitude of the stressor (Peters et al. 2011; Biswas et al. 2012). If features of soils and tidal water coverage remain, mangroves tend to recuperate by themselves. In some regions, mangrove forests are dynamics and suffer regular loss and regeneration, like in storm-subjected areas (Taylor et al. 2013; Villamayor et al. 2016) and in macrotidal areas, like the AMMC (Nascimento et al. 2013). Some degraded areas can self-recover, albeit more slowly than assisted restoration with several functional traits returning early also in natural mangrove recovery (Proffit and Devlin 2005; Ferreira et al. 2015). However, the destruction/degradation of soils and alterations to hydrology delays or even impair mangrove recovery, and management can be necessary to restore the forest functions. Climate change is responsible for losses of mangroves (storms, floods) but also for area expansion and increase in productivity, in some places, following sea water intrusion and soil salinization by sea level rise (Gilman et al. 2007; Godoy and Lacerda 2015; Castañeda-Moya et al. 2020). Some gains in mangroves area have been detected in specific locations, with South America having the higher rate of gain in respect to loss (0.48), followed by North and Central America and Caribbean (0.26) and Southwest Asia (0.17) (Worthington and Spalding 2018).

Natural colonization and regeneration of damaged forests is driven by the settling of waterborne propagules (or seedlings) in sites where soil and hydrological conditions are within their physiological tolerance and rooting capacity, modulated by the variable effects of salinity on germination, effects of tides on dispersal in littoral zone and rooting, and herbivory over survival (Tomlinson 2016). Some propagules are viable for several months, e.g., *Rhizophora*, which float until reaching suitable soil, strand against roots or strand and lean in a vertical position facilitates rooting. This genus is dominant in Neotropical mangroves, since seedlings are resistant, long-term viable, and grow fast. White mangrove *Laguncularia racemosa* is a pioneer species that grows fast, but their small seeds are more sensitive to desiccation, burying, flooding, and consumption by herbivore crabs (Elster et al. 1999; Delgado et al. 2001; Ferreira et al. 2019). Propagules of *Avicennia* are also small, able to settle on drier and/or hypersaline soils, but are also subjected to premature death by burying and consumption by crabs (Smith et al. 2019; Ferreira et al. 2019). Other herbivore groups can influence vegetation structure and ecosystem function in mangrove forests (see Cannicci et al. 2008 for a review). *Avicennia* and *Laguncularia* small propagules are more rapidly harmed by fungi and decomposers in sediments, so the 'window' for settlement and development is smaller (Rabinowitz 1978; Elster et al. 1999).

However, the ability of *Avicennia* species to sprout from damaged stems provides an important advantage for this genus growing after partial clearing or in areas affected by frequent storms (Duke 2001). Mature *Rhizophora*, on the other hand, lacks epicormic resprouting, and in regions with frequent great storms and/or where they are predicted to increase, a stand of these trees could be seriously damaged and may not recover (Villamayor et al. 2016; Fickert 2020). *L. racemosa* can colonize disturbed/impacted areas (Soares 1999) and grow fast. However, a high abundance of propagule consumer crabs (mainly the mangrove crabs (*Goniopsis cruentata* and *Ucides cordatus*)) can influence seedling recruitment through direct consumption of propagules, and this ultimately influences tree diversity, forest structure, and biomass stocks (Ferreira et al. 2019). Increasing focus on the influence of Brachyuran crabs over forest regeneration, nutrient cycles, biomass, architecture, and other functional aspects shows that biotic factors can be important shapers of mangrove community structure and characteristics, such as physical-chemistry (Lee 1998; Araújo et al. 2012; Pülmanns et al. 2015: Ferreira et al. 2019).

In other places, direct (deforestation, pollution, occupation) and indirect (climate change) human pressures are sources of mangrove degradation and mortality (Ferreira and Lacerda 2016). Aquaculture, industrialization, urbanization (including damming), and conversion to agricultural areas have been the main drivers of degradation of mangrove in Brazil (Lacerda et al. 2019). Conversion rates in relation to regional forests extension are higher in the Northeast and Southeast states (SAE, ETC, and SGC). Depending on the level of degradation, abandoned shrimp ponds, if opened to input of tides and estuarine waters, can self-regenerate in 15–30 years. This seems to be the first and most effective solution to begin restoration (Matsui et al. 2010; Primavera et al. 2011; López-Portillo et al. 2017). Eliminating impairing or stressing factors, e.g., dams or altered hydrology, allows the influx of estuarine water to ponds and can supply areas with waterborne propagules, enabling recovery.

Silvicultural practices are more extensive in Asian mangroves, mainly for fuel wood, but also for non-timber products, and even in alternative environmental-friendly shrimp breeding practices (Shearman 2010; Günter et al. 2011; UNEP 2014; Bosma et al. 2014). Managed plantings to obtain fuel, fence posts, poles, charcoal, construction timber, and sawn timber are reported from Venezuela and Puerto Rico (Hamilton and Snedaker 1984). However, there are no data in Brazil concerning traditional silvicultural practices in mangroves.

20.9 Threats and Conservation

Mangroves in Brazil are under increasing pressure from a combination of human activities, such as increased aquaculture, coastal development, agricultural runoff, pollution, and intensive aquaculture, and many of these human impacts are exacerbated by global climate change. Threats from the range of anthropogenic activities are varied and conservation strategies diverge, depending on the location along the coast because of the variation in state protection (either through laws or implementation), climatic differences, cultural dependency and local exploitation, and level of historical degradation. The diversion of freshwater for irrigation and land reclamation has resulted in the loss of extensive tracts of mangrove forests, as has been seen in Asia (Ward et al. 2016). In the last few decades, large areas of mangrove have been converted to aquaculture, fundamentally altering the nature of the habitat. Table 20.3 presents a summary of the major drivers of impact and response of mangroves, in order of importance, in the different sectors of the Brazilian coast.

Climate change predominantly affects the AMMC and the SAE, both with broad coastal plains where erosion of the sea margin has been witnessed, because of sea level rise, and landward migration following saline intrusion resulting from enhanced ocean forcing due to increasing heat accumulation in the South Atlantic (Sutton and Hodson 2005; Lee et al. 2011). These effects are exacerbated by land use changes in the SAE resulting from river damming and decreasing annual rainfall (Andrade et al. 2018). Conversely in the SGC and SQC regions, an increase in the frequency and intensity of the El Niño—Southern Oscillation is likely to increase in precipitation and hence terrestrial sediment runoff, which may in part off set the impacts of sea level rise through net increases in elevation.

The SAE harbours over 96% of Brazilian aquaculture shrimp production. The extension of farms has increased from less than 500 ha in 2000 to over 20,000 ha in 2020, becoming the principal threat to mangroves along this sector of the Brazilian coast. Shrimp aquaculture affects mangroves by conversion and degradation of mangrove functioning augmenting nutrient fluxes to adjacent estuaries (Sá et al. 2013; Marins et al. 2020) as well as the erosion of fringe forests adjacent to input and output channels (Godoy et al. 2018) and, to a lesser extent, illegal deforestation and conversion of mangroves to shrimp ponds (Ferreira and Lacerda 2016). Direct mangrove conversion causes the release of GHG and the remobilization of carbon and trace metals causing eutrophication and contamination (Lacerda et al. 2019). Recent changes that weakened Brazilian legislation will increase the threat to mangroves from aquaculture (Oliveira-Filho et al. 2016).

The ETC presents a large variability of habitats and environmental settings occupied by all mangrove typologies. Therefore, impacts from human activities are largely site-specific. An important driver of degradation along this coast is the relatively recent development of the offshore oil industry, which has become a potential threat to local mangroves, either due to accidents involving oil spills or from associate inland processing and transport facilities.

Table 20.3 Summary of major drivers of impact and response of mangroves, in order of importance, in the different sectors of the Brazilian coast

Sector	Major drivers	Impacts
All	Legal insecurity	Loss of buffering transitional zones at the land–mangrove interface Reduction of mangrove area and loss of ecosystem services and of species Altered ecosystem functioning
AMMC	Climate change	Erosion of the sea margin Landward migration following saline intrusion
	Harbour	Forest conversion, restricted to, but significant, in the São Luís Bay, Maranhão state. Small harbour facilities in other sites in the AMMC
SAE	Aquaculture	Forest conversion causing the release of GHG Reduced mangrove functioning as filters Remobilization of carbon and trace metals Eutrophication and contamination
	Climate change	Increased intensity and frequency of extreme drought reducing mangrove productivity Decreased rainfall, reducing continental runoff affecting sedimentation equilibrium Erosion of the sea margin Landward migration following saline intrusion Hypersalinity
	Damming	Reduce continental runoff affecting sedimentation/erosion equilibrium
ETC	Oil and Gas industry	Forest conversion Contamination
	Tourism	Forest conversion Inadequate solid waste disposal, plastic pollution
	Urbanization	Forest conversion Inadequate solid waste disposal, plastic pollution Untreated sewage causing eutrophication
	Industrialization	Pollution by trace metals and POPs
SGC	Urbanization	Inadequate solid waste disposal, plastic pollution Untreated sewage causing eutrophication
	Industrialization and harbour	Pollution by trace metals and POPs
	Climate change	Decreased productivity due to extreme weather events

The SGC is the most urbanized and industrialized sector of the Brazilian coast, many studies have reported a 50% area loss of their mangroves since Brazil's colonization. Most threatened mangroves are those occurring in the inner sector of bays (e.g., Guanabara and Sepetiba in Rio de Janeiro State and Santos in São Paulo state). Apart from receiving drainage from megacities, they also host large port and harbour facilities. Inadequate solid waste disposal and untreated sewage effluents, cause eutrophication in most protected coastal areas, while plastic, trace metals, and persistent organic pollutants (POPs) released in urban and industrial effluents contaminate local biota. Important to note is that this is the only sector of the coast in which mangroves cannot migrate inland following sea level rise because of the presence of a coastal mountain chain (Serra do Mar) along this entire region.

20.10 Global Change and Its Effect on Mangroves

Impacts from global climate change on the coastal zone have received increasing attention due to the potentially serious socioeconomic implications, mostly associated with sea level rise, increased air, and water temperature, increased atmospheric CO_2, changes in the quantity and quality of continental runoff, and changes in the frequency and intensity of extreme weather events, and alterations in ocean currents. The geographical distribution of mangrove forests at the continent–ocean interface makes them more likely to respond to pressures resulting from global climate change (Alongi 2015; Ward et al. 2016; Lacerda et al. 2020; Ward and Lacerda 2021).

Impacts from climate change, modulated by human activities in the coastal zone, has been observed to have profound effects on the area and extent of mangroves in Brazil (Godoy and Lacerda 2015). In the Bragança region, along the AMMC, severe erosion induced by coastal retreat of 32 km^2, between 1972 and 1998, resulted in a loss of mangrove area of 12 km^2 (Souza Filho and Paradella 2003; Souza Filho 2005). The causes of these dramatic changes are still poorly understood since there is no local historical series of surface current data, of tides, waves, and winds, but they may be associated with the increase in ocean forcing on the continental shelf as suggested by Dias et al. (2013). Despite the reduction in mangrove cover along that coast, there was an active growth of mangroves in the adjacent and topographically higher plains previously occupied by grasses and forbs. This herbaceous vegetation that once occupied an area of 8.8 km^2 in 1972 is greatly reduced and could be covered by mangroves in the next two decades (Rubén et al. 2002). Remotely sensed mappings of the entire AMMC, which harbours almost 750,000 ha of mangroves, showed that between 1996 and 2008, the total mangrove area increased by 718.6 ha (Nascimento et al. 2013).

Mangroves along the northeastern coast of Brazil (SAE) showed increasing expansion landward. Maia et al. (2006) compared satellite images with previously published maps based on radar images and aerial photographs from 1978 (Herz 1991) and showed a 35% increase in mangrove area (444–610 km^2) over a period of 25 years, although the different methodologies and instrumentation may have overestimated this expansion. In the Jaguaribe River, in the SAE region, there was an increase of 24.15 ha in estuarine intertidal area between 1992 and 2003 due to higher sedimentation in the estuary because of upstream damming and a decrease in annual rainfall over the basin caused by global climate change. The resultant intertidal islands are quickly colonized by mangrove vegetation (Godoy and Lacerda 2014). In addition, the residence time of materials and water in the estuary is increasing due to increasing ocean forcing on the continental shelf, because of excess heat accumulating in the South Atlantic due to global warming (Dias et al. 2013; Lacerda et al. 2013).

In another estuary along the SAE, the Pacotí river estuary, Lacerda et al. (2007) showed mangrove expansion over abandoned salt pans and on recently enlarged estuarine beaches and islands, also resulting from decreasing and regulating fluvial flow. These new areas were quickly occupied and fixed by mangroves, expanding the forests from 71 ha in 1958 to 142 ha in 1999 and further expanding to 144 ha in 2004.

The most outstanding mangrove expansion, more than 400%, occurred at the Aracatimirim River Estuary, also in the SAE, between 1993 and 2008. Most of this increase occurred in recently formed intertidal islands colonized by mangroves. The capture of sediments within this small, pristine estuarine basin, is accelerated due to increased choking of tidal estuarine waters by ocean forcing associated with the global climate change.

A landward expansion of mangroves is an expected response to changes in the transport of water and sediment volume caused by land use changes within watersheds, aggravated by sea level rise, given available space in coastal plains, as in the AMMC and SAE. In the other two regions, tertiary cliffs (ETC) and mountains (SGC) will limit landward migration and mangroves will not be able to cope and adapt to sea level rise (PBMC 2013; Godoy and Lacerda 2015; Ward and Lacerda 2021). Another typical response to global warming is the poleward migration, extending mangrove forest limits, observed in the Western North Atlantic (Cavanaugh et al. 2014; Saintilan et al. 2014). In the Western South Atlantic, the latitudinal limit of mangroves at Laguna, in the state of Santa Catarina (SGC), monitoring showed no significant poleward migration of mangroves. These stunted forests (3.0–5.0 m tall), currently limited by extreme weather conditions in winter, may expand Southwards following an increase in air and ocean surface temperature, the reduction of the frequency of frost events, stronger influence of the Brazil Current, and a weakening of the Falkland current (Soares et al. 2012).

Notwithstanding the apparent balance between erosion due to sea level rise and landward expansion of mangroves in Brazil, some recent results showed a drastic reduction of mangrove productivity due to extreme drought and winds. Litterfall production of undisturbed forests in Espírito Santo state in the ETC, was reduced from 575 to 169 kgC ha^{-1} $year^{-1}$ following these extreme events (Gomes et al. 2021). A recent extended drought (>3 years) strongly impacted mangroves in the Jaguaribe estuary in the SAE (Godoy et al. 2018). Unfortunately, no long-term historical monitoring of the effects of these events on mangroves is available, although their frequency has increased in the past 100 years (Alvalá et al. 2019; Marengo et al. 2018; Lacerda et al. 2020).

Based on the results available so far, the impacts of climate change on mangrove forests in Brazil in relation to coverage and distribution are different according to the sector of the Brazilian coast (Godoy and Lacerda 2015; Godoy et al. 2018). Along the north quaternary coast, including the AMMC and SAE, mangroves are expanding landward, as a result of rising sea levels and saline intrusion. In the semi-arid coast of the northeast, as a result of annual rainfall and the damming of rivers have accelerated the expansion and land migration, but recent developments in shrimp farming may limit this process (Lacerda et al. 2021). In many areas, however, mangrove erosion at the mouth of rivers and on deltaic islands counterbalances forest cover increase locally, as reported for the AMMC (Souza Filho and Paradella 2003; Souza Filho 2005).

In contrast, along the SGC, mangroves are disappearing faster as a result of rising sea levels and increasing frequency of extreme weather events. These drivers are exacerbated by strong human pressure, particularly urbanization, within the narrow coastal plains they colonize. At the southern tip of this zone, although mangrove forests could expand poleward following increased temperature and lower frequency of extreme cold events, this is not currently occurring (Soares et al. 2012). Along the ETC, few data exist on the response of mangrove to climate change. The high diversity of habitats, morphological configuration of this region, and the enormous but varied pressure of anthropic vectors may result in different responses at the local level, and no general trend can be evidenced.

The most cost-effective and efficient measure for carbon sequestration management is to conserve existing mangroves (Murdiyarso et al. 2012; Friess et al. 2019). Around 39% of remaining mangroves globally are inside protected areas (PAs), mainly in the American Continent and South Asia, where Brazil, Indonesia, and Mexico have the largest extensions of mangrove PAs (Worthington and Spalding 2018). However, this does not necessarily mean full protection, but might at least lower levels of degradation. Most mangroves and other coastal-marine PAs are governed centrally by the state, and their effectiveness is limited by being isolated within environmental agencies with poor interinstitutional collaboration, conflict among several management authorities, jurisdictional and regulatory ambiguities, and pressure of economic sectors (Ferreira and Lacerda 2016). In other cases, degradation outside PAs can impact protected mangroves, as is the case of impacts over estuarine or coastal mangroves by alteration of water or sediment flux, or pollutants upstream. Effectiveness of PAs has been under discussion in Brazil, where some of them lack management plans and have adopted rather vague fishery management measures so far (Lopes et al. 2011; Magris and Barreto 2021). Although community-based protected areas have been somewhat debatable by some environmental authorities, on the basis of difficulties of enforcement and monitoring, in many areas they have shown shown good conservation results (Ferreira and Lacerda 2016; Zaldívar-Jiménez et al. 2017).

20.11 Conclusions

At present, with the third highest extension in the world, Brazilian mangroves are unevenly distributed along the coast, showing distinct biological and ecological characteristics which results in different responses to environmental impacts. Distribution and composition of these forests along the Brazilian coast are a result of geologically recent changes in sea level. Biomass, productivity, and carbon allocation in Brazilian mangroves vary among different regions, depending on latitude, climate, and geomorphology. Mangroves are resilient communities that can recover after certain disturbances. Overall, mangroves in Brazil have so far been less affected by anthropogenic impacts, compared to other mangroves worldwide, due to the remote location of large and well-protected forests along the Amazon Macrotidal Mangrove Coast (AMMC). Major forest area loss and degradation, however, has been occurring on the South Granitic Coast, the most urbanized and industrialized sector. Today, most impacts on mangroves are typically indirect, such as contamination by effluents from industrial, urban, and aquaculture sources. The associated loss of ecosystem services includes reductions in primary productivity, carbon storage, response to other stressors, the efficiency of the estuarine filter, and biodiversity and abundance of subsistence use of estuarine and marine species. The extent and duration of the damage depends on the occupation of degraded areas by other activities that can permanently impair ecosystem function. The most cost-effective and efficient measure to protect goods, services (like carbon sequestration management), and ecosystem functionality, is to conserve the existing mangroves. Most recent changes in the environmental legislation and the growing impacts from global climate change have created a scenario where even the relatively pristine and remote forests along the AMMC are being threatened. Also, this scenario reduces the effectiveness and extension of some societal responses towards conservation and sustainable management and leads to increasing rates of mangrove loss. On the other hand, efforts and initiatives of mangrove regeneration and replanting need to be urgently expanded also by institutional support, since increasing public awareness of the mangrove importance to marine ecosystems and to livelihoods at the land–ocean interface may contribute significantly to reducing the pressures and minimize their impacts on mangroves in Brazil.

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Chapter 21
Cameroon Mangroves: Current Status, Uses, Challenges, and Management Perspectives

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Abstract Cameroon has mangrove cover of more than 220,000 ha contributing to 6% of African coverage, the sixth largest in Africa and the largest in Central Africa. They have great structural peculiarity with diverse flora and fauna being the most giant in Africa and among the biggest and tallest in the world reaching over 1 m in diameter and 60 m in height especially around the Wouri estuary. The mangrove forests encompass three ecosystem types: freshwater (from inland hydrology), brackish water, and marine water systems. Cameroon mangroves provide a wide range of vital ecosystem goods and services valued at 77,040,470,590 FCFA (US $154,080,941)/year, i.e., 8,347,128 FCFA (US$ 16,694)/ha/year. The tangible ecosystem services (provisioning services) or natural resources provide a means of subsistence for more than 30% of the population of the country living in coastal areas dependent on its resources, particularly wood and non-timber products including fishery products. The non-tangible services include: regulatory services ranging from stabilization of the coastal zone, carbon sequestration to improvement of the micro- and macro-climate; support services, supporting the food chain, spawning ground, and habitat for many other marine and aquatic animals; and cultural services as a venue for spiritual activities of most festivals with enormous potential for ecotourism and environmental education. Mangrove and associated coastal areas have been lost annually at more than 1% in Cameroon but this varies greatly within the regions increasing in Rio del Rey area by 9.4% per year, declining in the Cameroon Estuary by −1.1% per year with Douala-Bonaberi (country's economic capital and most populated city) area being the highest hotspot reaching −6.2% per year, and—2.1% per year in the Estuary of Ntem. The driving factors are coastal population growth, urbanization, fish processing, sand extraction, and uncoordinated policies and government economic coastal development programs including accentuated pollution from extractive and processing industries. Government and partners have contributed significant efforts currently putting over 92% of mangrove

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coverage under various conservation and sustainable management practices: conservation as national park (50.3%), Ramsar sites and under sustainable management (70.8%) as communal forest (35.2%), and community forest ownership (7.5%). Many awareness campaigns, sustainable utilization, and restoration and research initiatives have also been embarked upon. What really remains is the enhancement of management effectiveness of these mangroves through policy amelioration and coordinated efforts of the different stakeholders in the perspectives of sustainable management of Cameroon mangroves. Recommendations are made to attain this goal.

Keywords Mangroves · Livelihoods · Conservation · Sustainable use · Cameroon

21.1 Introduction

Cameroon's coast stretches over a distance estimated at 500 km and represents almost 1/5 of the whole coastline of the Congo Basin. The mangrove forests and associated coastal forests cover an important part are hugely important but a globally threatened ecosystem (Dahdouh-Guebas et al. 2020). These mangroves are mainly grouped in three areas (mangrove blocks) from north to south: Rio Del Rey estuary contiguous with the mangroves of the Niger Delta in Nigeria; the estuary of Cameroon; and the Ntem estuary comprising mouths of Rivers Nyong, Lekoundjé, and Ntem contiguous with the mangroves of the Equatorial Guinea Republic. In recent years, the mangroves of Cameroon have been subject to several types of studies including descriptive studies to show biological and socio-economic potential to highlight their ecological role in coastal protection, studies to show changes in these areas and policy oriented studies. Some mangrove sites have been or are the subject of resource conservation projects. All these interventions facilitated the acquisition of an advanced level of knowledge of these important ecosystem resources.

In this chapter, within the framework of exploring the biodiversity, livelihoods, and conservation concerns of mangroves, available relevant data are exploited to present the current extent and distribution of mangroves in Cameroon; status of mangrove biodiversity and ecosystem services; values and current uses of mangrove; threats, challenges, and drivers of mangrove biodiversity loss; conservation, sustainable utilization, participatory management, and research initiatives in place to addressing the threats and challenges; and recommendations with perspectives for sustainable mangrove management.

21.2 Extent and Distribution of Mangroves in Cameroon

21.2.1 Site Description of Cameroon Mangroves

Cameroon mangroves stretch from the Southwest, through the Littoral to the South regions. According to Letouzey (1968), they extend inland from the coast for up to 30 km and are largely riverine establishing along coasts and creeks. According to the latest comprehensive mapping of mangroves of Cameroon by MINEP-RCM (2017) exclusive mangrove areas in Cameroon cover over 221,162 ha (or 234, 293 ha including associated coastal forests) commonly grouped into three main blocks. In the North Rel Del Rey estuary mangroves cover 180,538 ha (45.5%) (or 131,497 ha including associated coastal forests) from the mouth of Rivers Akpa Yafe and Ndian from the border with Nigeria contiguous with the mangroves of the Niger Delta, Lokele, and Meme right up to the West of Mount Cameroon (Fig. 21.1). In the center Cameroon estuary mangroves, 93,549 ha (42.3%) (or 99,730 ha including associated coastal forests) stretching from the bay of River Bimbia, the islands formed by the tributaries of Rivers Mungo, Wouri, and Dibamba and around the cities of Limbe, Tiko, and Douala to River Sanaga estuary. In the south Ntem estuary mangroves, 2354 ha (1.1%) (or 3067 ha including associated coastal forests); occurring in patches from the south of River Sanaga, the Nyong estuary, Lokounje to Ntem River on the border with Equatorial Guinea (Fig. 21.1).

21.2.2 Panoramic Appraisal of Cameroon Mangrove Blocks

21.2.2.1 The Rio del Rey Estuary Block

This is situated in a landscape of the hottest biodiversity spots of Cameroon, downstream from Cross River, Korup and Takamanda forests, in the shadow of Mt. Cameroon and in the wettest corner of Africa with 4–10 m of annual rainfall, it is the biggest mangrove zone; parts of it are still very much intact, with a known quality of fisheries grounds. It is probably one of the best conserved mangrove ecosystems on the Western and Central Africa Coast. It lies in a presently remote and undeveloped area of the Cameroon coast with a number of oil palm plantations at its periphery, no important roads or other infrastructures cross this area and only a few small human settlements. Since the 1960s there has been some off-shore oil exploitation in the Gulf of Guinea at a distance of 100–200 km off the Rio del Rey coast. The area includes Bakassi Peninsula that was recently included in the Cameroonian territory. There is a large potential for more oil and gas exploitation in this important biodiversity hotspot. The area is sparsely populated with about 400,000 inhabitants; there are 115 mangrove villages with a total population of 250,000 people, about 70% of whom originate from Nigeria. The trend towards fragmentation and overexploitation are important especially with the nearby Nigerian town of

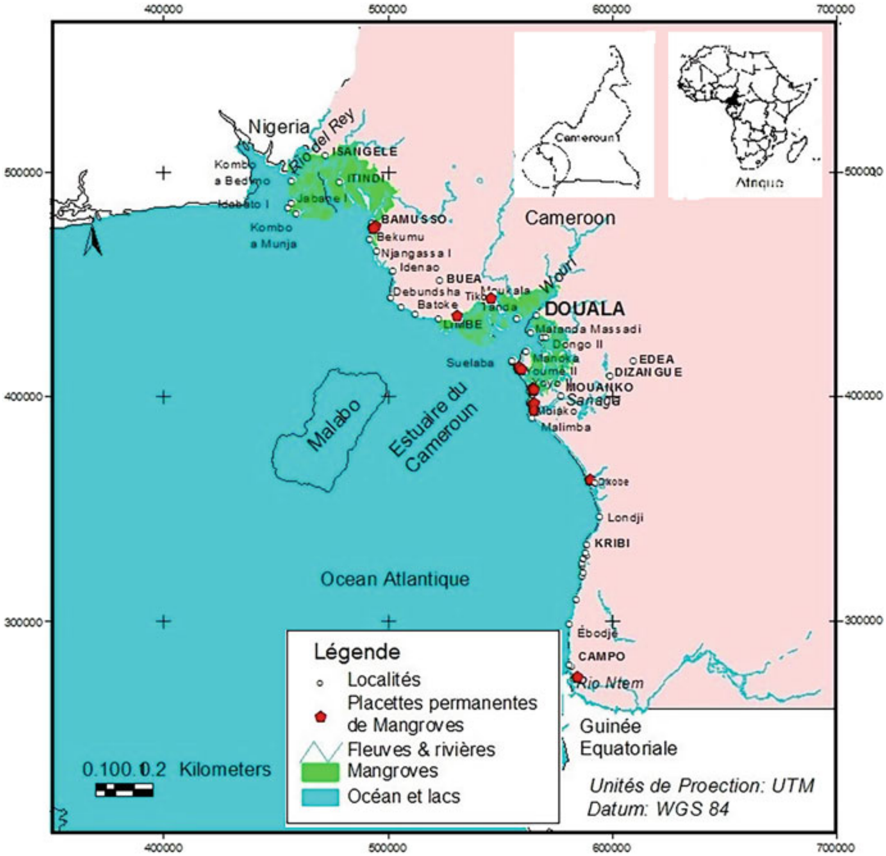

Fig. 21.1 Map showing the distribution of mangroves of Cameroon

Calabar with a population estimated at two million people. The main activities are fisheries, fish drying, and exploitation of mangrove poles for building and trading. The main markets being the Nigerian town of Calabar. This presents a trend towards fragmentation and overexploitation of its resources. The remoteness and insecurity of the area make it a real challenge to build up good relationships with local fisheries communities and develop a comprehensive conservation and development strategy. The area faces a big threat from fast advancing alien invasive palm *Nypa fruticans* introduced in near-by Nigeria in 1902 from SE Asia as is carried by the governing Beneguela Current and is dominating indigenous mangrove species. Conservation activities by the government, NGOs, private sector, and local communities have been focusing on baseline studies and projects geared towards the creation of the Ndongore national park covering over 121,590 ha including the marine and mangrove zone (Cameroon's third marine park) with about 72,000 ha of mangroves. Part of the Rio Del Ray area has also been enlisted as Cameroon's fifth Ramsar Site from recent water bird and wetlands surveys undertaken by WWF with NGOs including the Cameroon Wildlife Conservation Society (CWCS).

21.2.2.2 Cameroon Mangrove Estuary

It is a confluence zone of the estuaries of five important Cameroon rivers: River Bimbia, Moungo, Wouri, Dibamba, and Sanaga. Sanaga the largest of the Cameroon rivers, at 918 km long arises from the Adamawa foothills and drains an area of 133,000 km^2, serves as a lifeline on which millions of Cameroonians depend. The main dam for hydro-electricity production at Edea some 30 km from Douala supplies electricity to more than half of the Cameroon population and the main aluminum company ALUCAM is also located at Edea. Although being the largest mangroves in Africa reaching 60 m in height and more than 1 m in diameter due to fluvial influences, they are the most threatened mangroves in Cameroon from development pressures, pollution, and natural resources extractive activities. They are heavily surrounded by many towns including the Cameroon economic capital and industrial city of Douala with over two million people, a very good road network links the various towns including Kribi, Yaounde (300 km away from Douala), Tiko, Buea, and Limbe and the Douala International Airport. It has a number of oil palm plantations at its periphery belonging to a number of national and multinational companies including CDC, SOCAPALM, FERME SUISSE, and SACAFAM. The area is also under petroleum exploration and exploration activities of PECTEN and PERENCO companies. The area is heavily populated with about 3.2 million inhabitants with some 62 mangrove villages with total population of 63,000 people in foreign dominated (about 70%) fishing camps. The main activities are fisheries, bivalve exploitation along the Sanaga mouth with annual tonnage of 8000 t, fish drying and exploitation of mangrove poles for building, and trading. The main markets are Douala, Yaounde, Bafoussam, Bamenda, etc. along a very good road network. Mangrove conservation activities are mainly undertaken by CWCS since 1997 within the Douala-Edea wildlife Reserve being raised in 2018 to the status of a national terrestrial and marine park (first marine park) covering about 263,000 ha with about 40,000 ha of mangroves. Lake Ossa and lower Sanaga sections of the park are being designated as Ramsar Sites.

21.2.2.3 Ntem Mangrove Estuary

These discontinuous patches of mangroves (around rivers Nyong, Lonkonjie, and Rio Ntem) with about 3200 people are intact though also close to the Chad-Cameroon Pipeline and Kribi Deep Sea Port project areas. The area also has a number of oil palm plantations belonging to SOCAPALM at its periphery with good roads or other infrastructures crossing the area. The main activities are fisheries, trading, and especially beach tourism that attract thousands of nationals and international tourists with tourism infrastructures especially hotels in Kribi and environs. WWF is active in the area with its Kudu Zombo program within the Campo Ma'an landscape covering over 700,000 ha including Rio Ntem and parts of Kribi coast. Also prominent among actions are those of the Marine Turtle initiative of a local NGO, Association Nationale de Protection des Tortues Marines "KUD'A TUBE" at Ebodjie between Kribi and Campo whose actions have led to the Gazettement of the second marine park in Cameroon—the Manyange na Elombo-Campo Marine National Park covering 110,300 ha with 1500 ha of mangroves. The Rio Ntem mangrove section of Equatorial Guinea is a Ramsar Site and presents a good trans-border opportunity to the designated Cameroon section of the Ramsar site. The recent effort of the Cameroon government to classify the Lokoundjé Falls as a World Heritage site was highly contested by the local population. But the Kribi Deep Sea port project has been largely successful.

21.2.3 Status of Mangrove Biodiversity and Ecosystem Services

Generally, the biodiversity of mangroves in Cameroon is well known with studies carried out largely in the mangrove area of the Cameroon estuary than in other mangrove blocks (Rio Del Rey and Ntem blocks). Although this can pose a real problem of comparison between the blocks in terms of biodiversity, mangrove biodiversity is quite specific in flora and fauna and can be found the same everywhere.

21.2.3.1 Floristic Diversity

In the current state of knowledge on taxonomy, six native and 1 introduced species form the woody floral background mangroves of Cameroon in particular and those of the entire Atlantic coast in the Gulf of Guinea in general. Native species are: *Rhizophora racemosa, Rhizophora harrisonii*, *Rhizophora mangle* (Rhizophoraceae), *Avicennia germinans* (Avicenniaceae), *Laguncularia racemosa*, *Conocarpus erecrus* (Combretaceae), and the introduced species, *Nypa fructicans* (Arecaceae). The characteristic zoning pattern around a mangrove formation can only be on a relative scale because in many places there is no clear zoning. The spatial distribution of vegetation is very irregular because different species tend to settle on different micro topographic configurations and different soil types (Mbog 1998). In most sites, *Rhizophora racemosa* occupies more than 90% of the areas covered by mangroves, followed by *Avicennia germinans* which takes about 5% (Ajonina 2008). *Rhizophora* therefore forms the most extensive stands of mangroves, with many almost monospecific areas. This monospecificity is generally followed by a mixed zone where all Rhizophoraceae (*R. racemosa*, *R. harrisonii*, and *R. mangle*) can be found mixed, where the sediments are more consolidated but still flooded daily by the tides.

Above this level, where tidal flooding is reduced, there is usually an area with *Avicennia germinans* which can be monospecific, or mixed with *Laguncularia* or *Conocarpus*. A study carried out in the mangroves of Bakassi, Limbé, Douala, Tiko, and Kribi on the vitality of mangroves shows a preponderance of the species *Rizophora mangle* in a good number of sites (ONEQUIP 2009).

It should be noted that *Nypa fructicans*, which is a species native to Asia and introduced into these formations, occupies the ground considerably after *Rhizophora*. The other companion species covers a small area, *Avicennia germinans* which is recognizable by its pneumatophores and the presence of salt crystals on its leaves is easily distinguished in the landscape of *Rhizophora racemosa* to which it is often mixed by its lighter green leaves. This difference could be demonstrated even on false color infrared aerial photos, where *Rhizophora* appears a brighter red than *Avicennia* (Mbog 2002).

The six species of mangrove trees live most often, in association with more than 40 other species of plants considered as "companion species" or "accidental." Among these plants considered to be the most commonly observed are: *Drepanocarpus lunatus*, *Dalbergia ecastaphylum*, *Hibiscus tiliaceus*, *Phoenix reclinata*, *Acrostichum aureum*, *Pandanus candelabrum*, *Raphia palma-pinus*, *Sesuvium portulacastrum*, *Alchornea cordifolia*, *Annona glabais*, *Elogeliis guinensista*, *Athona glabais*, *Elogeliis guinensista Bambusa vulgaris*, *Cocos nucifera*, *Eremospatha wendlandiana*, and *Guiborutia demensei*.

21.2.3.2 Phytoplankton

More than 430 species of phytoplankton have been counted and can be grouped into three classes: Bacilliophyceae, Dinophyceae, and Cyanophyceae. These different species have different levels of affinities for pollution with the majority (39%) in the neutral class. Most of the species are comparable to those recorded by Folack (1989) and Mbeng et al. (2017) in the Kribi area in the south and in the Limbe region in the west, respectively.

21.2.3.3 Fauna Diversity

Mangroves are habitats that are home to an important, very varied and diverse fauna that colonizes each ecological niche. Important by both the number of species and the economic value of most of them. In general, a distinction is made between aquatic fauna, terrestrial fauna, and avian or aerial fauna.

Aquatic Fauna are the most important in terms of both the number of species and the economic value of most of them.

Zooplankton Some 205 species of zooplankton are found in the mangroves of the Cameroonian coast with different levels of affinity for pollution.

Aquatic Mammals These include manatees (*Trichechus senegalensis*). According to the NGO APEMC (Association for the Protection of Marine, Coastal and Wetlands Ecosystems), manatee populations were estimated at more than 2500 individuals around the 1980s across the country. Today, due to intensive poaching by fishing communities, this species no longer reaches 1000 individuals across the country. This species is in danger of total extinction in Cameroon if no action is taken because according to monitoring carried out by the NGO Cameroon Wildlife Conservation Society (CWCS 2000–2006), at least 30 individuals, caught in fishing nets are killed per year in the Douala-Edea National Park. Its flesh is appreciated by local riparian communities, and its oil highly prized in cosmetics. The Otter (*Aonyx capensis microdon*) is another species that lives in the mangroves of Cameroon. It is found in abundance in the mangroves of the Douala-Edea national park.

Regarding cetaceans in the nearby sea, eight species have been identified by Ayissi et al. (2014): Atlantic Humpbacked dolphin (*Sousa teuszii), Delphinus capensis,* Short-beaked common dolphin (*Delphinus delphis), Tursiops truncatus, Stenella attenuata,* or *S. frontalis, S. coeruleoalba,* Humpback whale (*Megaptera novaeangliae),* Sperm whale (*Physeter macrocephalus),* some have been observed by AMMCO (African Marine Mammal Organization) using local fishers surveys with a flexible mobile application software siren (https://ammco.org/telecharger_siren).

Reptiles For the purpose of feeding and nesting, five species frequent the mangrove area, namely the green turtle (*Chelovia vydas*) (Cholomïdae), olive turtle (*Lepido Chelys olivarea*) (Cholomidae), leatherback turtle (*Dermochelys coriacea*) (Dermochelidae), hawksbill (*Evert vuoduelys imbricaba*) (Cholomidaes), and loggerhead turtle (*Carrella Carrella*) (Cholomïdaes) (Ayissi et al. 2003).

Crustaceans Present in all mangrove waters, crustaceans are numerous in the mouths of estuaries. The most commonly observed in the country's mangroves are: *Nematopalemon hastatus* (crayfish or Njanga) heavily used in artisanal fisheries by local communities. *Penaeus kerathurus* or tiger shrimp, *Parapenaeopsis atlantica*, *Panaeus notialis*, and several species of crabs that inhabit the mangroves such as *Ginossis pelii, Cardiosoma armatum, Geryon maritae, Panopeus africanus*, etc. (Ngo-Massou et al. 2014).

Molluscs The most characteristic molluscs of Cameroonian mangroves are oysters or gastropods. They are found in all the mangroves of Cameroon where some 39 species have been recorded (Ngo-Massou et al. 2012; Kottè-Mapoko et al. 2017) with some re-descriptions of certain genera by Shahdadi et al. (2019, 2021). Among the molluscs that live in these mangroves we can cite: *Pugilina morio, Thais coronata, Corbula trigona, Crassostrea gasar, Littorina angulifera, Loripes aberrans, Nassa argentea, Neritima adansoniana, Tagelus angulanus, Pachymeliana fuscatus, Pachymeliana aurita Shut callifera,* and *Melampus liberanus*.

Fish In mangrove areas, we find pelagic fish species: Clupeidae, Scombroidae, Sphrynaedae, Cichlidae, Trichiuridae, Carangidae and demersals: Scianidae, Pomadasidae, Lutjanidae, Cynoglossidae, Dsyatidae, Ariidae., Polynemidae. Among these species, pelagic fish (*Sardinella maderensis* and *Etmalosa fimbriata*) are the most exploited, especially in the Bakassi area (ONEQUIP 2009). Nearly 40 species of fish are found in the mangrove area. The most commonly observed fish species are: *Caranx hippos*, *Caranx* spp., *Trachinotus teraia*, *Tilapia* spp., *Pellonula afzeliusi*, *Arius gigas*, *Arius heudeloti*, *Arius parkii*, *Ethmalosa fimbriata*, *Sardinella ceperensis*, *Plectorhynolithus*, *Pomadotasysus* spp., *Pomadotasysus* spp., *Dentex congoensis*, *Ilisha africana*, *Galeoides decadactylus*, *Polydactylus quadrifilis*, *Pomadasys jubelini*, etc.

Regarding sharks, three species have been identified: *Carchahinus leucas* and *Shpyrna* sp. (Hammerhead shark); *Squatina aculeata* (Saw-back shark) and *Squatina oculata* (smoothback shark) in the Bekumu area (Rio Del Rey).

Terrestrial Fauna Ecological studies on the terrestrial fauna of mangroves in Cameroon still remain very disparate, very specific, descriptive, and not very in-depth. However, they make it possible to distinguish between resident fauna and non-resident fauna. The resident fauna takes into account that located in the canopy of mangroves (mammals, reptiles, nesting birds, insects). Non-resident fauna is that which is not fixed in the intertidal zone or the zone of tidal waves. It includes migratory birds and euryhaline animals that spend part of their life cycle in mangrove ecosystems. Data on microfauna and mesofauna are rarer. Despite these reserves, the terrestrial fauna of mangroves is very diverse. It is made up of reptiles, mammals, birds, and insects.

The Mammals Included in this group are blue monkeys (Cercopithecidae), antelopes such as sitatunga (*Tragelaphus spekei*), aquatic buckskin (*Hyemoschus aquaticus*), bush pigs (*Potamochoerus porcus*), etc.

Reptiles Also include the dwarf crocodiles (*Osteolaemus tetraspis*), giant crocodiles (Crocodylia), monitor lizards Nile (*Varanus niloticus*), African pythons (*Pithon selae*), aquatic cobras (*Boulangerina annulata*), etc.

Avifauna Observations show that many birds (more than 125,000 individuals counted in January 2014 are found on the Cameroonian coast, CWCS 2014) live permanently in the mangroves which are roosts for several endemic species and places of temporary accommodation for many migratory species. Species such as *Ardea goliath* (Heron), *Bubulcus ibis* (Cattle keeper), *Butorides stratus* (Gray heron with green back), *Egratta alba* (Egret), *Numenius arquata* (Courbis), *Phala crocarax africanus* (Cormorant) and *Tringa* Sp., African Open Beak and Scissor Beak. Pelicans (*Pelicans refeseus*), black herons (*Egretta ardesiaca*), intermediate egrets (*Egretta garzetta*), sea swallows (*Sterna* spp), petrels (*Oceanites oceanicus*), knights (*Tringa* spp), African comorants (*Phalacrocorase africanus*), sandpipers (*Calidris* spp), riverbanks (*Limosa numernius arguata* and *N. phalopus*), plovers (Charadrius), gray parrots with red tail (*Psittacus erithacus*) hornbills, giant blue turacos (*Corythaeola cristata*), wild ducks, etc. are also encountered. There are over

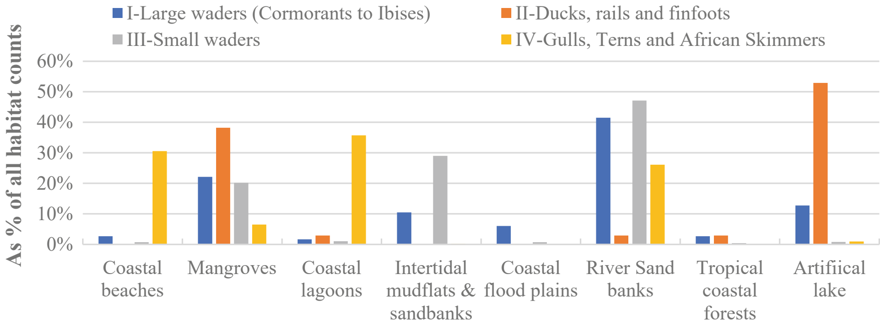

Fig. 21.2 Habitat distribution of bird groups (Ajonina et al. 2021)

70 species of water bird that annually visits mangroves and the coastal zone (Ajonina et al. 2003, 2009a, b, 2020, 2021) with up to 40% affinity to the mangrove habitats (Fig. 21.2).

21.3 Stand Structural Characteristics: Stand Densities, Volume, Biomass, and Carbon Stocks

Generally, there is a great structural peculiarity of mangrove stands in the Central African coast stretching from Cameroon to Angola in being the most giant in Africa and among the tallest in the World (Blasco et al. 1996) reaching over 1 m in diameter and 60 m in height (Akendengue et al. 2021) (see Figs. 21.3 and 21.4) especially around the Wouri estuary in Cameroon where mangrove trees of up to 131.7 cm were measured in Ngalaberi mangrove creeks (009°40′41″E, 3°49′19"N) (Ajonina 2008).

The average stand density in intact mangrove forests is 3255.6 trees/ha with 80% of the trees in the lower 10 cm diameter class, the standing volume of 427.5 m^3/ha corresponding to aboveground biomass of 305.7 Mg/ha (Ajonina et al. 2014a, b). Together with dead wood, the total biomass of vegetation reached a maximum of 825.0 Mg/ha. The total stock of carbon in the non-degraded mangrove ecosystem was estimated at 1520.22 ± 163.93 Mg/ha with 982.49 Mg/ha (65%) below ground (soil and roots) and 537.73 Mg/ha (35.0%) in the aboveground biomass (Ajonina et al. 2014a, b). Though the carbon sink potentials of mangrove are high (Ong 1993), the biomass is among the highest in the world and superior to adjacent Congo Basin Rainforest (Fig. 21.5).

Fig. 21.3 Atypically giant mangroves of central Africa (tree measured in a permanent sample plot at Campo (Ipono)-Ntem estuary, Cameroon)

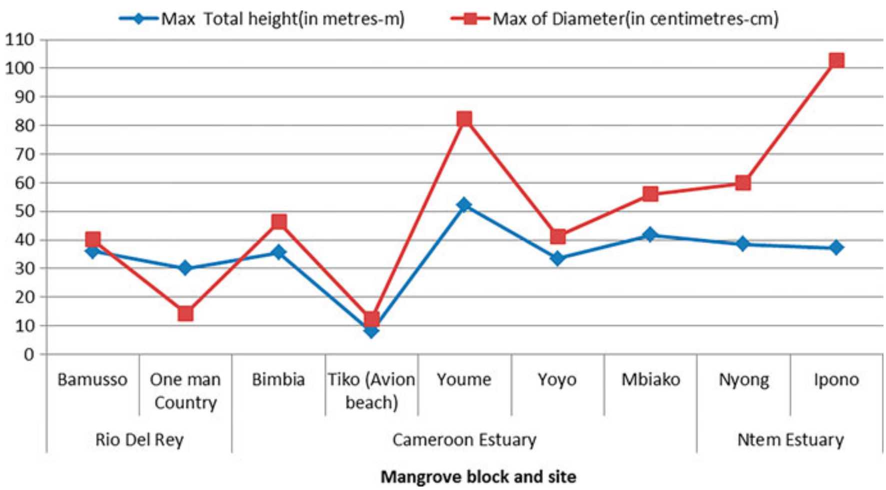

Fig. 21.4 Mangrove landscape profile in Cameroon: height and diameter from permanent sample plots (Ajonina and Chuyong 2017)

21.3.1 Mangrove Forest Dynamics and Carbon Sequestration

Regeneration data are obtained from the analysis of satellite images between 2000 and 2015 and those of population dynamics are derived from the analysis of data from permanent plots established along the Cameroonian coast between 2001 and

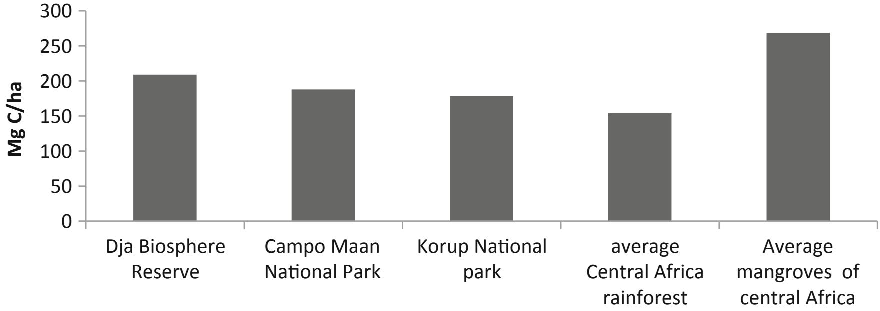

Fig. 21.5 Comparison of aboveground carbon stocks from selected terrestrial rainforests in the Congo basin and mangroves (Ajonina et al. 2014a, b)

2003 and remeasured once every 2 years by the CWCS (Ajonina 2008; Ajonina et al. 2014a, b; Ajonina and Chuyong 2017).

The annual regeneration rate varies from 0.0 to 2.0% in the Rio Del Rey estuary, 0.0 to 8.0% in the Cameroon Estuary, and 0.0 to 0.5% in the Ntem Estuary. The mortality rate in Cameroon mangrove forest is located between 0.0 and 14.0% per year (Ajonina and Chuyong 2017; Ndema et al. 2014; Ajonina and Chuyong 2017) (Fig. 21.6). The average mean annual increment in diameter (MAI) for primary and secondary stems under different management regimes was 0.15 cm/year.

This translates into annual increments of aboveground biomass above and below ground of 12.72 Mg/ha/year and 3.14 Mg/ha/year, respectively. Carbon sequestration rates vary by forest conditions, the aboveground parts (AGC) had proportionately higher sequestration rate (6.36 MgC/ha/year) compared to soil carbon pools (BGC). Undisturbed forests sequester on average of 16.52 MgC/ha/year against 0.39 Mg C/ha/year and 6.89MgC/ha/year by the highly and moderately degraded systems, respectively. The average rate of carbon sequestration for all forest conditions was 7.93 Mg C/ha/year, a figure comparable to similar studies elsewhere in Malaysia (Ong 1993), Thailand (Komiyama et al. 2005), and Kenya (Kairo et al. 2008).

21.4 Values and Current Uses of Mangrove

21.4.1 Mangrove Goods and Services

Mangroves provide many ecosystem goods and services that can be used directly or indirectly by local coastal communities (Ajonina and Eyango 2014) to guarantee their livelihood and ecological securities. Mangroves provide vital ecosystem services which include: tangible ecosystem services (provisioning services) or natural resources as a means of subsistence for 30% of the population of the country living in coastal areas dependent on its resources, particularly wood and non-timber

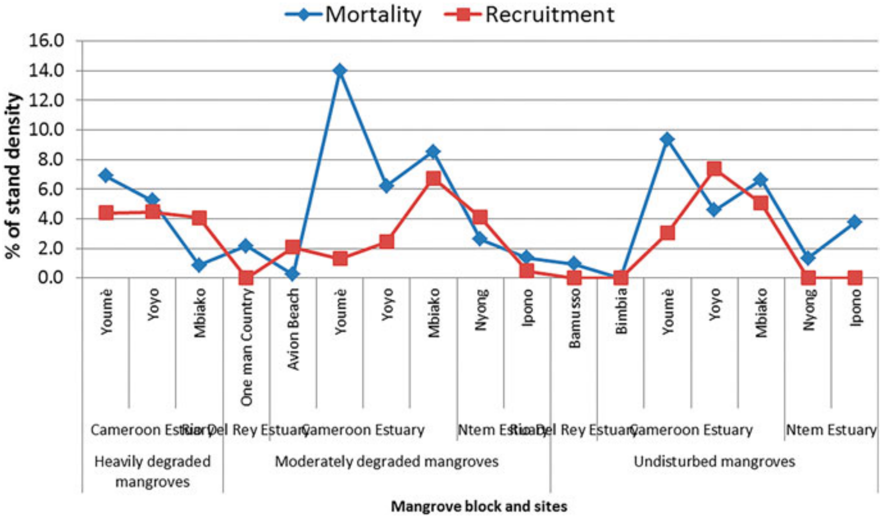

Fig. 21.6 Patterns of mortality and recruitment across Cameroon coast (Ajonina and Chuyong 2017)

products including fishery products; non-tangible services including: regulatory services ranging from stabilization of the coastal zone, carbon sequestration to improvement of the micro- and macro-climate; support services, supporting the food chain, spawning ground and habitat for many other marine and aquatic animals; and cultural services as a venue for spiritual activities of most festivals with enormous potential for ecotourism and environmental education (Dahdouh-Guebas et al. 2020).

21.4.2 Economic Valuation of Mangrove Ecosystem Services

According to a study in the Douala-Edea area (Noumeyi 2015), mangrove provisioning ecosystem services had an estimated monetary value of 2,027,761,495 FCFA (US$ 4,055,523)/year, i.e., 3,627,107 FCFA (US$ 7254)//ha/year. Regulating ecosystem services in turn had monetary value of 75,012,709,095 FCFA (US $ 150, 025, 418)//year, i.e., 4,720,021 FCFA (US $ 9, 440)/ha/year. Overall, the value of some goods and services of this ecosystem was 77,040,470,590 FCFA (154, 080, 941)/year, i.e., 8,347,128 FCFA (US $ 291, 467)/ha/year. In a similar study conducted in the Wouri area (Ajonina et al. 2015), the flow of people and goods across the Wouri River generates a turnover of 12,252,600 FCFA (24,505 USD)/canoe/year at Youpwé and 3,896,286 F CFA (7792 USD)/canoe/year in Akwa Nord.

21.4.3 Socio-Economic Elements and Main Uses of Natural Resources

The mangrove zone covers three regions (states/provinces) (the Southwest, the Littoral, and the South) spread over six Divisions (or departments), 24 districts, and 166 villages/districts in Cameroon. There are approximately 3,600,000 people in and around Cameroon's mangrove ecosystems, with 300,000 people (7.6%) residing in the mangrove formations (Ajonina 2010). The zonal distribution is very inequitable. In fact, about 70% of the population of the Rio Del Rey area live in mangroves, against 2.5% for the Cameroon estuary area and 21.3% for the Ntem estuary (Table 21.1).

The coastal zone of Cameroon is very populated with regional capitals such as Douala, the country's economic capital, and major cities (Kribi, Limbe, Tiko, etc.). There are also many villages and hamlets as well as fishing camps. The mangrove area has about 15 local communities including 5 urban communes and 10 peri-urban communes surrounded by companies of natural resource extraction industries (petroleum, agro-industries, etc.) and other industries.

Although the mangrove is a fragile ecosystem, its richness in natural resources ensures that it performs several important functions for the life and ecological security of five million Cameroonians (30%) living in the coastal zone. They represent an important economic source, used for thousands of years by the coastal populations who depend on them and contribute to the improvement of their living conditions (Mbog 1999).

21.4.4 Fishing Practices in Mangrove Areas

Fishing is the main economic activity in the mangrove areas of Cameroon. Industrial fishing is quite limited. Conversely, artisanal fishing is very widespread and is practiced by fishermen attached to mobile or fixed camps. This activity is the driving force behind a chain of other activities that fall into what can be called the fishing industry.

According to studies carried out by CWCS in three fisheries (Suelaba, Yoyo, and Mbiako) in Douala-Edéa National Park, 54 species of fish are exploited (CWCS 2000–2006; Nanji 2007). In the Sanaga estuary, bivalves (oysters) constitute a great source of income for the local populations in the recession season (November–June) when it is estimated that more than 800 tons are exploited with an income of more than 500 million CFA francs. The men harvest the oysters, while the women are interested in the pulpit where they make the "soy" steaks (Ajonina et al. 2005).

The players in the fishing industry represent the largest group of operators of mangrove natural resources. This group is dominated by young people and singles, especially in Rio Del Rey where fishermen live in temporary camps, far from their families. In this area in particular, several villages disappeared with the Bakassi

Table 21.1 Population in and around mangrove areas in Cameroon (After Ajonina 2010)

Mangrove zone	Name of the municipality	Number of mangrove villages	Total coastal population	Mangrove resident population	
				Total	As % total coastal
Rio Del Rey estuary	Ekondo Titi	35	75,000	5000	6.7
	Bamusso	20	10,000	10,000	100
	Bakassi	45	150,000	150,000	100
	Idenau	4	30,000	20,000	66.7
	Subtotal	114	265,000	185,000	69.8
Cameroon estuary	Limbe 3 (Bimbia)	5	60,000	20,000	33.3
	Tiko	6	40,000	25,000	62.5
	Yabassi (Nkam)	3	30,000	500	1.7
	Dibombari (Moungo)	3	20,000	500	2.5
	Douala I	3	450,000	2500	0.6
	Douala II	2	600,000	1000	0.2
	Douala III (Inclue Dibamba) 9 9	6	800,000	5000	0.6
	Douala IV	5	450,000	3500	0.8
	Douala V	3	800,000	3500	0.4
	Douala VI (Manoka)	22	45,000	15,000	33.3
	Ndonga (Dizangue)	3	5000	1000	25.0
	Mouanko	13	10,000	6000	60.0
	Subtotal	74	3,310,000	83,500	2.5
Ntem estuary	Kribi I/Lokonjie	4	10,000	1000	1 0.0
	Campo	6	5000	2200	44.0
	Subtotal	10	15,000	3200	21.3
Total		188	3,590,000	271,700	7.6

conflict and the military occupation. Conversely, an increase in the number of fishermen were noted in the villages and camps around Isangele, Baracks, Bamousso, Bekumu, etc. In the militarized zone temporary camps move regularly from place to place, with less and less sustained fishing effort.

Foreign fishermen are generally professionals in this industry. However, they are generally the poorest of the other economic players in the fishing industry and dream of defending their interests within professional associations. This organization can also help reduce the abuse of authority and harassment that could also come from a few crooked agents of the maritime brigade or the merchant navy. Finally, it can help organize (regulate) fishing and reduce conflicts between artisanal fishermen and industrial fishermen.

Opposite the group of fishermen, there is the group of fishmongers ("buyam-Sellam") and processors of fishery products. It is dominated by women who work full time sometimes following the fishermen and therefore moving from one fishing camp to another depending on the season (case of processors). In Rio Del Rey, the processors are often the wives of the fishermen and sometimes the fishermen themselves smoke their catches and then sell them on site to arriving traders or in periodic markets.

In the Wouri estuary area, the fishmongers of fresh fish, using motorized canoes, travel to the fishing grounds themselves to buy and collect the fishermen's catches. Overall, while fishermen are dominated by foreigners (Nigerians), fishmongers and processors are dominated by nationals.

The major problems facing fish wholesalers and processors relate to capital. The construction of smokehouses and other accessories is often expensive. Preserving fresh fish is even more complex and costly.

21.4.5 Sand Mining

Sand mining is one of the important activities in mangrove areas and especially those close to large cities (Douala, Tiko, Edéa, etc.). In Youpwè (Douala), artisanal sand extraction is estimated at more than 4 t per day (ONEQUIP 2009). The main quarries around Douala are located in sites such as Modeka Bay, Youpwè, Bonabéri, Akwa Nord at the level of the Wouri river mangrove. Like the mangrove poles exported to Nigeria, sand from the Cameroon estuary is currently exported in large quantities to Equatorial Guinea for construction.

21.4.6 Sectors of Industrial Development and Pollution

Among the other activities practiced in the mangrove areas, there is industrial agriculture led by companies such as SOCAPALM, HEVECAM, or CDC which cultivate oil palm, rubber, banana, or tea at an industrial scale. These companies are more located in the coastal strip of the Southwest region and are also around Kribi covering thousands of hectares. They use a lot of fertilizers, pesticides, and herbicides, the leaching of which affects the mangrove areas. These are products which generate nitrites, phosphates, chlorine and which are likely to cause eutrophication phenomena in the middle of mangroves. The result is a reduction in the natural productivity of these environments. The industrial plantations found in the area are home to important worker towns. This diversity bodes well for a wide variety of activities, including those in rural areas and those in industrial and tourist towns.

21.4.7 Urbanization and the Development of Human Settlements

In the Rio Del Rey estuary, the development of fishing camps has hardly any relation to the phenomenon of urbanization. The management of the border conflict between Cameroon and Nigeria has also helped to reduce fishing camps. However, it should be noted that the development of the Bakassi peninsula through the creation of an administrative unit can change this trend.

In the Cameroon estuary, the situation is presented in different terms. Indeed, the space of the estuarine system is considered by the Douala as a property bequeathed to them by their ancestors. However, it is one of the components of the public domain of the Cameroonian State because, according to the ordinance no ° 74/2 of July 6, 1974 fixing the state system, "the banks of the mouths of the rivers under the influence of the sea" form an integral part of the maritime public domain. Article 2 of the aforementioned ordinance prescribes that property in the public domain is not subject to private appropriation. We can therefore realize, faced with the reality on the ground, that the mangrove area of Douala is therefore the subject of illegal trade and we observe an advance of the city towards the mangroves which are gradually nibbled, destroyed, reclaimed for residential buildings.

Fishermen are no longer the only inhabitants of the mangrove area, which in some places is radically changing their activities. The canoe makers, outboard mechanics, pure farmers, the fisheries administration, and traditional authorities who presented themselves as facilitators of the fisheries sector are no longer the only players. The space is also occupied by commercial or industrial activities.

21.4.8 Logging and Forest Resource Management

According to Mbog and Ajonina (2007), the first systematic industrial exploitation of mangroves in sub-Saharan Africa began in the Gulf of Guinea in Cameroon, on the island of Manoka in 1919 when the Société Nationale de Bois du Cameroun obtained forest concessions to exploit mangrove wood and built a sawmill on this island. Considerable amounts of *Rhizophora racemosa* (red mangrove) timber have been removed. This wood extracted from mangroves was used for railroads (trans-Cameroonian), and for the manufacture of wooden barrels used for the conservation of palm oil and table wine in Europe.

Today there is large-scale commercial or industrial exploitation of mangrove timber in two aspects: fuelwood and timber. This is done using power saws by highly organized groups of non-fishermen from the surrounding villages and outlying neighborhoods. Two categories of mangrove logging are distinguished: Manual artisanal logging using rudimentary equipment carried out by fishing communities, especially women; and modern logging with sophisticated modern equipment carried out by groups of loggers who wholesale or retail their timber to all segments of the population. These two types of exploitation have a significant impact on the mangrove ecosystem.

Logging activity which accompanies fishing is well established throughout the mangrove zone of Cameroon. Around all the fisheries, the search for wood (cutting and collecting) is daily. The wood is used for smoking fish, for the construction of smokehouses, for the construction or repair of houses, for the manufacture of canoes, for the production of latex which is used for coloring and preserving fishing nets, etc.

Mangrove wood is also cut and sold in towns for use as poles in urban constructions in Cameroon and Nigeria. Due to all these solicitations, the timber trade between the villages and all along the coast is flourishing. *Rhizophora* (red mangrove), one of the most abundant species in the Cameroonian mangrove, is also the most used. Trees 10 to 20 cm in diameter are cut into pieces of 1.5 to 2.5 meters maximum, to facilitate transport by canoe. In Cap Cameroon, these small farmers are even organized within an association, the "Firewood Cutters Union."

In the Rio Del Rey area, marked by large fishing camps and an absence of large towns, the production of wood for smoking fish represents the bulk of the cuts because housing construction is relatively limited. This trend may change with the development of the administrative center of the Bakassi Peninsula.

Conversely, in the southern part (Cameroon estuary, Manoka island, Souélaba peninsula), permanent habitation is more common and a lot of wood is consumed in the form of planks. In the areas surrounding the mangroves of Douala, the harvesters have the habit of penetrating the mangroves in order to make their choice on old trunks which, by falling, cause the fall of other trees and thus create large gaps in which rush the winds. This activity, which is accompanied by the use of chainsaws, is tending to become almost semi-industrial near Douala. Statistics on logging are difficult to collect for an activity recognized by its practitioners as illegal. Although this activity is done outside the law, the points of sale exist and are for some maintained by a game of corruption between the operators and the control services.

The extraction of *Rhizophora* bark for the exploitation of tannin has also been practiced in Cameroon following analyzes showed a generally high level of tannin (10–30% of the dry weight). Documents show an export in relation to the total wood removed (Mbog 1999). Today, the exploitation of mangrove wood is based in the Douala-Edea Fauna Reserve on the cutting of red mangroves, which are used for smoking and preserving fishery products, for cooking food in households, the construction of housing huts (lumber or poles), and the manufacture of fishing gear and handles of work tools.

Non-Timber Forest Products (NTFPs) have a great importance in the traditional life of the communities bordering the Mangroves. Mangroves indeed offer a wide range of Non-Timber Forest Products (NTFPs) which greatly contribute to the survival of poor local communities and create opportunities in the national and international market. Some of these products are consumed in the daily diet and some in cases of extreme famine. Picking edible species (leaves, roots, vegetable oils, wild fruits, mushrooms, saps, and others) is also a common practice. Initially intended for home consumption, some of these products are also marketed. Many

NTFPs are used in the cottage industry and in pharmacopeia for traditional medicine. Bark, leaves, roots, and fruits are used from mangroves.

The exploitation of the fruits (for consumption) and leaves (mat) of the Nipa palm (*Nypa fructicans*) depends on the presence of this species and concerns much more the mangroves of Rio Del Rey where it is abundant. Other NTFPs, notably rattan and palm trees found near or even within mangroves, are also subject to intensive exploitation and play an important role in the socio-economic life of the riparian populations.

The many species of lianas are used in the manufacture of furniture, or the making of roofs and hut structures. Today lianas and the leaf segments of *Nypa* and *Raffia* play an increasingly important role in the construction of huts, these lianas also represent a renewed interest in contemporary craftsmanship, in the manufacture of furniture and common objects of basketry.

Most of these products are found in large quantities in local markets and some for export, for example, the bark of *Rhzophora* spp. for tannin (farmers go through Nigeria for shipment), bunches of dried fruits of *Nypa fructicans* to decorate the interior, yohimbe peels.

21.4.9 Some Cultural Services

Mangroves have been of great immense cultural values as centers and sites for spiritual or ancestral worships including marking important cultural or traditional events. An example is the canoe races organized in the mangrove zone of Douala-Edea during the NGONDO festival a great traditional festival of the SAWA (Cameroonian tribe made up of clans: Bell, Bassa, Deido, Belle-Belle, Jebale, Akwa, Bojongo, and Moungo). They are organized during the first week of December or the last week of November. A race is estimated on average at 14,515,000 FCFA/year or a total of 7260 FCFA/ha/year of mangroves (Ajonina et al. 2013).

21.4.10 Ecotourism Potential

Though there is a scarcity of data on the recreation value of mangroves, available information indicate that mangroves are also potential tourism sites though not comparative to adjacent terrestrial ecosystems such as rainforests or other wildlife sanctuaries with bigger attractions. At the Ebojie Marine turtle site within the Ntem mangrove block, visitor records kept by the Association Nationale de Protection des Tortues Marines du Cameroun "Kud'A Tube" put an average number of visitors around ten visitors/month with a yearly total of 120 notwithstanding the COVID-19 crisis. Generally, tourism infrastructure in the mangroves is not yet fully developed and the potential has not yet been fully realized. Payments for Ecosystem Services

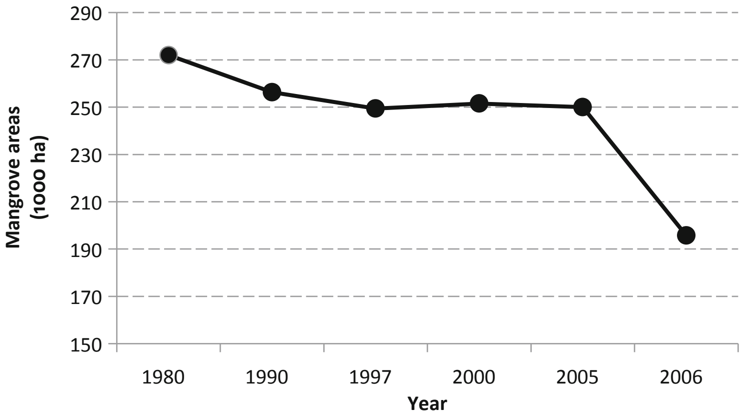

Fig. 21.7 Mangrove cover change in Cameroon (1980–2006) (UNEP-WCMC 2007)

(PES) schemes could explore improving ecotourism opportunities and income in the region.

21.5 Threats, Challenges, and Drivers of Mangrove Biodiversity Loss

21.5.1 Conversion and Degradation of Mangroves Ecosystems in Cameroon

According to the UNEP report (UNEP-WCMC 2007) of the mangrove cover study in West and Central Africa between 1980 and 2006, the mangrove cover in Cameroon in 2007 was about 200,000 ha having decreased by 28% between 1980 and 2006 in Cameroon (see Fig. 21.7).

21.5.2 Trends in Mangroves and Associated Coastal Forests Cover Changes

According to the analysis of satellite images between 2000 and 2015, mangrove land and associated coastal forests declined by −7.9% (−20,220 ha) in the period, i.e., −0.5% (−1348.0) per year. The rate of decline of intact mangroves is −0.8% (−501 ha) per year and increase in plantings and habitation of 3.7% (1492 ha) per year. Figure 21.8 shows intact mangrove swamps increase in the Rio del Rey area at 9.4% per year, decline in the Cameroon Estuary by −1.1% per year, and increase 2.1% per year in the Estuary of Ntem.

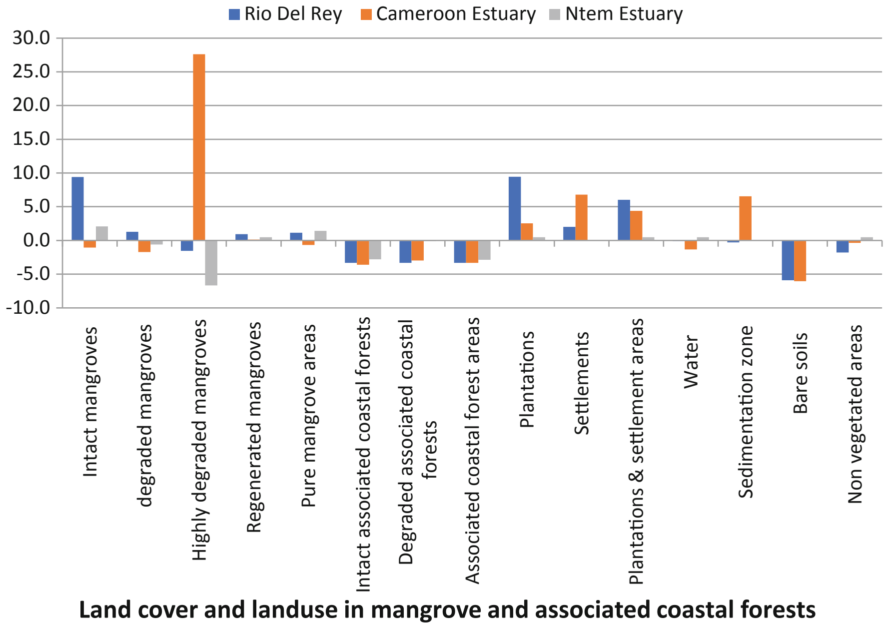

Fig. 21.8 Cover changes in mangrove and associated coastal forests in Cameroon

21.5.3 Causes and Consequences of Mangrove Conversion/Deforestation and Degradation in Cameroon

Population pressure on the unsustainable extraction of mangrove resources, the influences of invasive species, absence of a policy on mangroves, and climate change have been largely discussed as factors causing mangrove deforestation and degradation in Cameroon among others (Fig. 21.9).

21.5.3.1 Conversion or Deforestation of Mangrove Ecosystems in Cameroon

The direct causes being urban expansion and agricultural expansion especially the agro-industrial winter planting, palm groves, banana groves, etc. national companies: CDC and multinationals: SOCAPALM, FERME SUISSE, etc., and large-scale hydrocarbon exploration.

The main underlying factors are: demographic pressures, economic pressure, energy needs, and weak protection/legislation for mangrove areas—with large areas still unprotected except in the newly created Ndongoro National Park at the

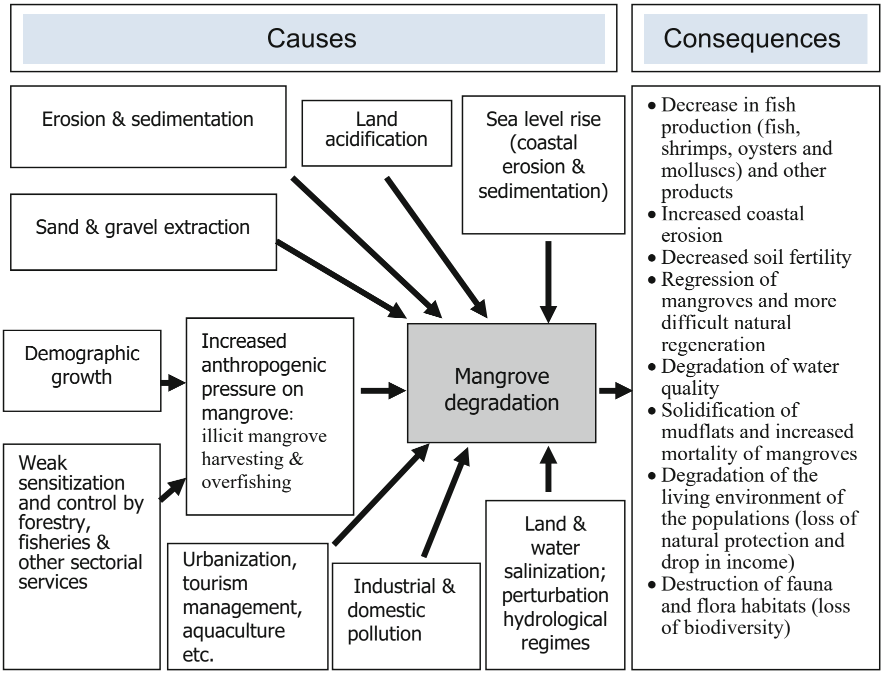

Fig. 21.9 Schematic diagram of mangrove degradation factors and consequences (Folock 2013 in MINEPDED 2014a, b, c)

border with Nigeria, Bois de Singe, Douala-Edéa National Park, and Campo Ma'an National Park on the border with Equatorial Guinea.

The majority of threats to mangroves from the main factors identified above include: urban infrastructure and agricultural development, eutrophication, and algal blooms—pesticides and fertilizers from large-scale plantations (rubber, palm oil, banana) in the coastal region of Cameroon. Invasive Species—The Nipa Palm is an introduced species, which has colonized several mangrove areas and competes with native mangroves, such as *Rhizophora*, water hyacinth (*Echorhina crassipes*) is also abundant. Most of the threats identified are well known, but not quantified and documented to better manage them.

21.5.3.2 Degradation of Mangrove Ecosystems in Cameroon

Mangroves are subject to degradation, the direct and underlying causes of which lie in two different (often linked) processes affecting mangroves: destruction or total degradation. In some cases, total destruction may be due to urbanization, large tourism or industrial enterprises, rice cultivation or their eradication to make way for shrimp farming. In other cases, partial deforestation is further aggravated by degradation of the mangrove (where most trees remain), due to activities such as oil or mining; we notice:

- physical degradation of mangroves by excessive cutting of mangroves;
- an alarming overexploitation under the action of a significant demographic growth and in the particularly difficult ecological and socio-economic context: the new habitat needs around the large agglomeration which cause significant clearing and an increase in energy and in natural resources especially sand;
- increasing pressure on fishery resources to which is added a misguided and technically unsuitable exploitation of mangroves (cutting of mangrove roots to harvest oysters, for example);
- The two groups of mangrove degradation factors (natural and anthropogenic) are summarized in Fig. 21.12 with the resulting consequences.

Among the direct factors of degradation are the energy needs of the growing urban and rural populations. Despite the abundant use of timber and non-timber forest products from mangroves, adequate legislation does not yet exist. On the socio-economic level, although the fishermen are a large majority of the professionals of the sector, the activity is dominated by foreigners confronted with problems of organization of the sector and by poverty compared to the other economic actors of the sector, the fishing industry.

The logging that is done throughout the mangrove zone of Cameroon in relation to the development of fishing camps (construction wood) and the intensity of catches (smoke wood) is in worrying proportions for nearby cities which also require mangrove wood in the form of poles or planks for urban constructions. Statistics on logging are difficult to obtain for an activity recognized by its practitioners as being outside the law.

Data on sand exploitation is insufficient to understand the impact of this activity, which is taken in great proportions around large cities. There are also reports of the export of mangrove sand from Cameroon to Equatorial Guinea. However, we can point out the importance of sandy beaches in the reproduction of certain species such as sea turtles.

21.5.3.3 Degradation Through Pollution of Mangrove Ecosystems

Mangrove zones are highly polluted especially from the Cameroon estuary with waters with Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) rates of more than 250 mg/l (Fonocho 2008; CWCS 2010) (see Figs. 21.10 and 21.11). This is largely due to the heavy concentration of industries and human activities in Douala City but also from agro-industrial plantations (SOCAPALM, HEVECAM, CDC) around mangrove areas including petroleum and gas exploration and exploitation that pour their wastes and effluents (liquid and solid) directly into the mangrove areas and the use of chemical products in fishing.

The degradation of mangroves and the disappearance of biodiversity promote eutrophication of the waterways as well as the suffocation of frequently flooded and

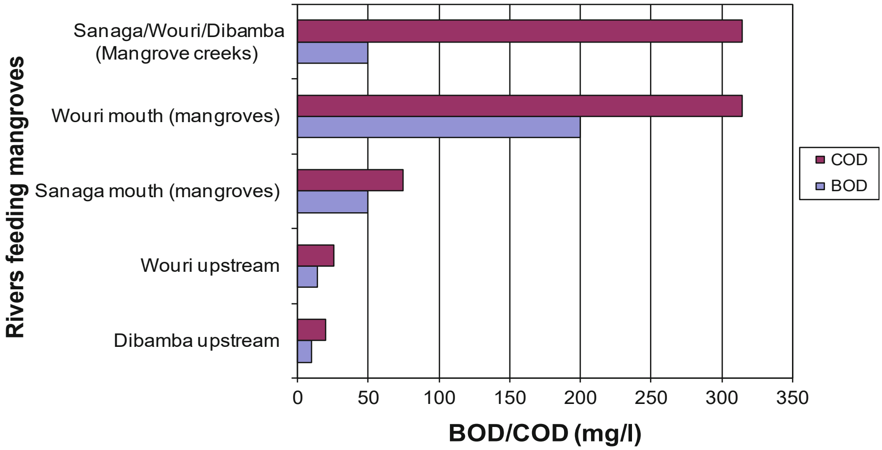

Fig. 21.10 State of pollution of the mangrove ecosystem of the Cameroon estuary [Sampling periods: August 2007 (mangrove areas) and August 2008 (upstream areas)], Fonocho 2008

Fig. 21.11 Pollution of mangrove ecosystems (Littoral Region: Photos NGUEKAM W.E in 2012)

non-oxygenated soils (Cam-Eco Study Report 2010). This is accelerated by invasive species such as water hyacinth and the Nypa palm (*Nypa fructicans*). The Indo-Asiatic mangrove palm *N. fruticans* introduced in Nigeria in 1906 has reduced native species diversity, with rapid invasion into Cameroon at the rate of 175 Nypa palm/ha/year (Moudingo et al. 2019).

The biochemical oxygen demand in the mouths and estuaries of the main rivers characterizing the hydrographic network of the mangrove zone exceeds the authorized limit value which is 250. The same is true for certain metals such as SS and coliforms whose concentration is well above the authorized limits.

Some pollutants result from the breakdown of chemicals used in industries. They fall within the range of molecules called persistent organic pollutants (POPs) which are harmful to the health of living beings in general and humans in particular. In the environment, they are deposited on vegetation, soils, and rivers and are absorbed by animals and fish which are then used as human food. They are the precursors of cancer in living beings and increase the vulnerability of infected species. Their presence in liquid and solid effluents justifies the absence of industrial waste treatment units. The lack of national standards on industrial waste management and the costs incurred by the recommended measures seem exorbitant for companies.

21.5.3.4 Policy, Legal, and Institutional Challenges to Sustainable Mangrove Management

Despite the ecological, economic, social, and cultural importance of Cameroon's mangroves, they are still not managed on a sustainable basis. Table 21.2 brings together the elements showing the strengths, weaknesses, constraints, and opportunities on policy, legal, and institutional framework relative to sustainable mangrove management in Cameroon.

The assessment of the implementation of national legal instruments reveals many gaps and shortcomings which demonstrate the efforts that remain to be made to have a complete and effective legal framework. Stakeholders' analysis within the mangrove zone carried out by Forkam et al. (2020) show that there are two major categories of stakeholders involved in the management of mangrove with different levels of involvement and interventions in the management process (Fig. 21.12). These are: (a) direct (primary) stakeholders (indigenous and non-indigenous of the local population and characterized by fishermen, fish smokers, mangrove exploiters including harvesters, processors, and marketers) concerned with mangrove exploitation and (b) indirect stakeholders made up of (secondary) stakeholders ("Development Agents" including NGOs, Research and Academic institutions, and the Council; "Policy Makers" who are parliamentarians and senators; and "Policy Implementers" being the Ministry of Forestry and wildlife "MINFOF," Ministry of Environment Nature Protection and Sustainable Development "MINEPDED," Ministry of Fisheries, Livestock and Animal Husbandry "MINEPIA," Ministry of Agriculture and Rural Development "MINADER," and Ministry of Tourism "MINTOUR") not in direct contact with the resource but playing service control law and enforcement role; and (tertiary) stakeholders living at the proximity of the mangrove forest who do not equally exploit the mangrove directly but they enjoy the indirect ecological benefit (positive externalities or green house benefits). They are mostly petty traders living in the area such as shopkeepers and fishmongers "buyam-sellam" either of smoked fish or fresh fish preserved in ice boxes mainly ecological services beneficiaries.

Currently, MINFOF, MINEPDED, and MINEPIA are major government institutional actors involved directly in the management of mangrove ecosystems and the coastline in Cameroon; other ministries are also involved, but to lesser degrees. Local administrations are not equipped to face the multiple environmental, economic, and social challenges of mangroves and the coastal zone in Cameroon. The institutional problems thus identified are:

Table 21.2 SWOT analysis of the policy, legal, and institutional framework relative to sustainable mangrove management in Cameroon

Strengths	*Weaknesses /failures*
• Favorable international context with ratified conventions including those that protect mangroves • The major players in mangrove management are globally known • Consultation frameworks exist or are under development and operate on a legal basis (decisions noting the collaboration frameworks, drafts of management documents for these frameworks, etc.) • Several donors are interested in the sustainable management of Cameroon's mangroves (FAO, GEF, etc.) • Projects have been carried out on the mangrove swamp and have made it possible to draw up documents from which we can draw lessons to be valued and lessons to be learned • The framework law which imposes the carrying out of EIAs on industrial enterprise projects • Political will with regard to participatory planning • Physical setting of mangroves fairly well known • Ongoing creation of more mangrove Ramsar sites	• Weakness in the EIA prescription for major investment projects or environmental audits for companies already established or lack of monitoring of the implementation of environmental management plans • Lack of specific regulations in the middle of mangroves (legislative texts) • Low valuation of traditional/indigenous knowledge and lack of an appropriate management model • Policy gap and multisectoral strategy for sustainable mangrove management • Weak local organization of the population • Lack of development initiatives led by the population • Mangrove not sufficiently taken into the country's planning and developmental processes, e.g., marginalization of the mangrove problem in current programs like the Forest-environment sectoral Programme (PSFE) • Lack of cross-border strategy to properly channel the activities of other nationals in mangrove areas
Opportunities	*Constraints/obstacles*
• Multiplicity of coastal projects that include mangroves at least at environmental impact scoping stages • Availability of the main stakeholders involved in supporting project actions (public services, international organizations and national NGOs, etc.) • Stakeholders are involved in the construction of various platforms on mangrove management, some with strong technical and organizational potential • Ongoing policy reforms in forestry and fisheries to integrate mangroves issues • Existence of NGOs active in the mangroves • Creation of more marine protected areas that include mangroves as integral habitats	• Existence of jurisdictional conflicts • Proximity to polluting companies • Population unemployment • Insecurity linked to border conflicts • Informality of several main activities in mangrove areas • Absence of reliable data and information especially on fisheries stocks and exploitation dynamics

- the lack of coordination and consensual planning of the initiatives undertaken by the actors who operate in the sustainable management of mangroves in Cameroon;
- conflicts of jurisdiction between the different administrations;

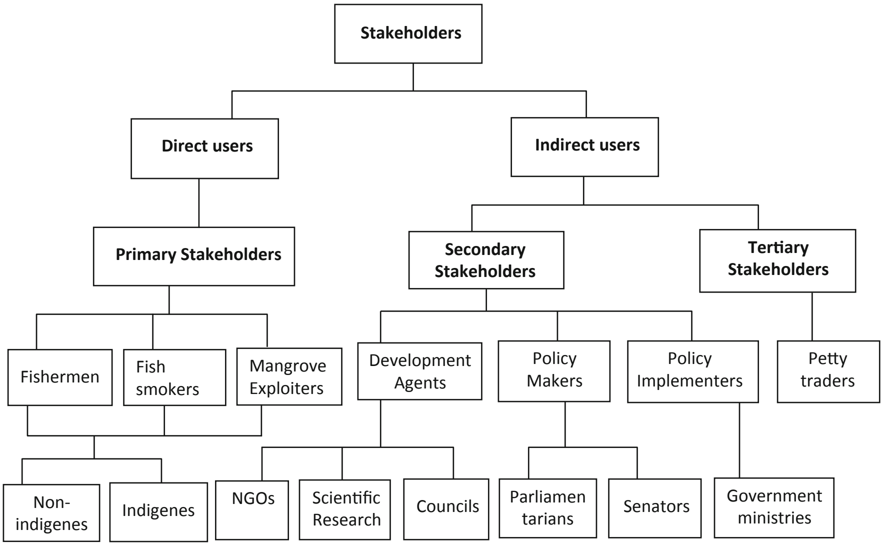

Fig. 21.12 Stakeholders involved in mangrove exploitation and management (after Forkam et al. 2020)

- a weakness in the prescription of Environmental Impact Studies and continuous/ permanent monitoring of environmental, sanitation, and public health indices;
- the inadequacy of national environmental and forest policies to the management of humid and fragile ecosystems in general, and particularly those of mangroves;
- A legal vacuum in terms of land: paradox of the location of mangroves in the maritime domain of the State and its exploitation or occupation;
- insufficient staff in certain sectoral services;
- the lack of adequate equipment for monitoring coastal areas including mangroves;
- the non-involvement and little consideration of the concerns and traditional knowledge of decentralized communities and local communities in the protection and management of mangrove ecosystems;
- the weak technical, organizational, financial, and managerial capacity of the riparian communities to enable them to fully participate in the protection and sustainable management of mangrove ecosystems.

21.6 Addressing the Threats and Challenges

The uncontrolled loss and degradation of mangroves have been met with efforts through projects that were mostly isolated and a lack of intersectoral coordination and a lack of access and dissemination of lessons learned from innovations and conservation initiatives, restoration, and sustainable use. The current management regime is discussed in the context of projects initiatives in these areas: conservation; awareness creation and environmental education tool for mangroves; restoration practices through mangrove reforestation; technology practices of sustainable use of mangrove resources; participatory management; and research and monitoring. These initiatives are to be strengthened and capitalized with a better coordination and integration of stakeholders in mangrove related projects.

21.6.1 Conservation

21.6.1.1 Creation of Mangrove Protected Areas

Some encouraging commitments have been made by the Cameroonian government with the support of civil society, especially international and national NGOs, for the conservation of mangroves through the creation of mangrove protected areas or their inclusion in the system of coastal protected areas. The Ndongore protected area project, or the Kribi Marine Park project with WWF support is considered and the inclusion of mangroves in the system of coastal protected areas of the Douala-Edea National Park as together they capture over 50.30% of the country's mangroves currently in marine protected area systems (Table 21.3). Also noting the full protection of certain species associated with the mangrove, for example: manatee, sea turtle, etc. In this regard, we should point out that there is a center in Ebodjé created by the ECOFAC program for the conservation of marine turtles, which has acquired many achievements, in particular in raising the awareness of populations and other tourists around certain hotels in Kribi. The awareness-raising tools developed encourage stakeholders to promote the release of young turtles accidentally caught in the sea. Donations of fishing gear such as nets have made it possible to consolidate this awareness-raising action. It is also a form of Payment for the Environmental Service (PSE). These initiatives should be strengthened and capitalized with better consultation and integration of stakeholders through mangrove projects and programs.

21.6.1.2 Ramsar Site Creation Initiatives

The government and partner have committed to designate Cameroonian territory under the Ramsar site regime, two sites have already been created and four are being created in the coastal zone to include more than 70.88% mangrove areas (Table 21.4).

Table 21.3 National parks, mangrove cover, and interventions in the coastal zone of Cameroon

Mangrove block	Name of National Park	Year of creation	Surface area (ha)	Mangrove (ha)	Sea (ha)	Mangrove (%)	As % National mangroves	Main intervening partners
Rio Del Rey estuary	Ndongore	Ongoing (Public Notice issued on April 2020)	121631.2	71,921	49670.2	27.35	32.52	CWCS/ MINEPDED
Cameroon estuary	Douala-Edea	Decree Oct 2018	262,935	39,202	97137.6	14.91	17.73	CWCS/ MINFOF
Ntem estuary	Manyange na Elombo-Campo	Decree July 2021	110,300	121	110,179	0.11	0.05	WWF/ MINFOF
Total			494,866	111,244	256,987	22.48	50.30	

Table 21.4 Ramsar sites, mangrove cover, and interventions in the coastal zone of Cameroon

Mangrove block	Name of Ramsar site	Year of creation	Surface area (ha)	Mangrove (ha)	Sea (ha)	Mangrove (%)	As % National mangroves	Intervening partners
Rio Del Rey estuary	Rio Del Rey estuary	2010	165,000	115,330	49,670	69.90	52.15	WWF/CWCS/MINEPDED
	Batouke	Ongoing	3900	100	780	2.56	0.05	AMMCO, MINEPED
	Subtotal		168,900	115,430	50,450	68.34	52.19	
Cameroon estuary	Nkam—Wouri	Ongoing	584,490	30,878	100	5.28	13.96	Université de Douala (ISH)/CWCS/WTG, MINEPDED
	Lower Sanaga Delta	Ongoing	120,000	10,331	20,000	8.61	4.67	CWCS/MINEPDED
	Subtotal		704,490	41,209	20,100	5.85	18.63	
Ntem estuary	Ntem River	2012	39,848	121	500	0.30	0.05	MINEPED
Total			913,238	156,760	71,050	17.17	70.88	

21.6.2 Development of Environmental Awareness and Education Tools for Mangroves

NGOs have launched several awareness campaigns on the importance of mangroves and the need to conserve and manage them sustainably. The broad sensitization undertaken by the Cameroonian Network for the Conservation of the Mangrove Ecosystem (RCM) through the biannual meetings of the executive committee, the organization of coastal forums, and rotatory exchange visits in the mangrove areas of Cameroon constitutes a major advance.

The NGO "Cameroon Environmental Watch" (CEW) based in Yaoundé and also a member of RCM has developed awareness-raising tools on mangroves as part of its awareness-raising project entitled "Plein Feux sur les Mangroves du Cameroun," a project carried out in all the coastal university towns of Cameroon (Buea and Douala) and in Yaoundé between 2007 and 2008. These tools were presented during the African regional meeting of RAMSAR in November 2007 in an exhibition stand visited by the Prime Minister and during the National Forest Forum in Cameroon in March 2010. These tools could be used to promote environmental education in conjunction with this NGO.

21.6.3 Mangrove Restoration Practices Through Reforestation

Participatory mangrove reforestation activities were carried out by Cameroon Wildlife Conservation Society (CWCS) in degraded mangrove areas of the Douala-Edea National Park (Moudingo et al. 2016) especially around the villages of Mbiako, Yoyo, Youmé, and Bolondo. These actions received initial support of the French NGO "Planète Urgence"/IUCN in 2005, UNDP between 2007 and 2009, WWF in 2009, MINEPDED, 2016–2019, thereafter Planète Urgence and INBAR within the framework of The Restorative Initiative (TRI) with IUCN partners recently. In total, more than 50 ha of degraded mangroves have been reforested with the techniques of nursery, direct planting with wildlings and propagules of *Rhizophora* and *Avicennia* with a success rate of over 80%. Lessons learned from these reforestation trials are documented in project reports and other publications (Moudingo 2010; Ajonina et al. 2016).

It should be noted the very remarkable efforts since 2010 of reforestation of more than 30 ha of degraded mangrove plots in the urban environment of Douala by the GIC-PPC under the cover of the RCM and technical assistance of the CWCS from which the private sector intervened, members of parliament, students of the Institute of Fisheries Sciences (ISH) of the University of Douala in Yabassi (planting over 25 ha of degraded mangroves).

In addition, pilot *Rhizophora* nurseries and mangrove plantation trials have been established with various successes by MINEPDED, CWCS, WWF, and the people of Campo Beach, in Kribi area by OPED in Rio Del Rey areas by CAMECO and other NGOs.

There is the need to consolidate these different isolated initiatives in order to appraise and document the level of success, best practices, and lessons learned to maximize their impact addressing restoration of degraded mangrove habitats.

21.6.4 Practices for Sustainable Use Technologies of Mangrove Resources

The mangrove wood use efficiency within the Douala-Edea area (Ajonina and Eyabi 2002; Feka et al. 2009; Feka and Ajonina 2011) for fish processing is the result of a technology introduced in 2000 by "Mangrove Action Project" (MAP) based in Los Angeles after its introductory experiences in Asia. The technology was therefore adapted in collaboration with the IRAD Oceanographic Research Center in Limbe with an expert on the subject and popularized in the Douala-Edea area. The principle is to close the opening around traditional smokehouses that source the smoke and thus prevent the leakage of thermal energy and to concentrate it more for smoking fish by reducing the effective smoking time. This technology reduces over 40% of the amount of wood used, thus limiting mangrove deforestation and combating climate change. It also has a positive impact on health as it lowers the rate of lung disease and reduces fires.

The material used to improve the smokehouse consists of mud bricks or planks closed on two sides with a sand hole to limit the leakage of thermal energy by conduction. The cost is estimated at 400,000 CFA francs (c200 US $) for smoking rooms using boards and one million (c500 US $) for those using bricks transported from the city. In terms of efficiency, they lead to a 30–40% reduction in wood used. In addition, the smoking time reduces from 21 h to 6–8 h. This had been the pivot for validation but has yet to be implemented by CDM which selected 400 smokehouses in nine villages of the reserve (Mbiako, Moloungo, Yoyo I, Yoyo II, Youmé, Bolondo, Nyangado, Sandjé and Sessioo) with potential generation of over 7800 tC/year. Similar efforts have been undertaken by the Women smoking fish around the mangroves in Kribi by OPED that earned them the prestigious 2016 Equador Prize.

The main problem with improved smokehouses is their acceptability and adoption by a large foreign and migrant population within the coastal areas.

21.6.5 Participatory Management

21.6.5.1 Through Mangrove, Marine, and Coastal Platforms

Backed by the 1990 law of Association in Cameroon, the process of institutionalization of the participatory management of mangrove ecosystems received an impetus with the establishment of various platforms at the local, regional, and national levels. At the local level, is the case of the Douala-Edea mangrove management committee (COPCVAM) led by the CWCS. This committee has three bodies, including the general assembly, the technical implementing body, and the village reforestation committee. The latter is made up of village chiefs, fishermen, fish smokers, and wood cutters. One of the key actions of this organization is the simple management plan which deals, among other things, with zoning and management rules according to an action plan drawn up during the general assembly held twice a year. The real challenge for COPCVAM with a multiplicity of actors (foreign fishermen, fish smokers, mangrove wood cutters) is to respect established management rules with appropriate organizational capacity.

At the regional level concerning the Cameroon three mangrove blocks, the platforms are created with the facilitation of CAMECO in a legalization process bringing together municipalities, public services, and the private sector. The Cameroonian Network for the Conservation of Mangrove and Wetland Ecosystems (RCM) with over 40 NGOs, community-based organizations, researchers, etc. remains the only national platform active in the conservation of mangrove ecosystems.

21.6.5.2 Through the Regime of Communal and Community Forests

The Law 94/01 of January 14, 1994 on Forests, Wildlife, and Fisheries provides for the creation for the benefit of local populations under a given council (municipality) a communal forest to an undefined extent and communities of community forests of up to 5000 ha for legal entities (NGO, CBO, etc.) within a community. Community-based mangrove management initiatives have been undertaken by certain riparian populations including Manoka in the sixth district of Douala; Canton Bakoko in the third district of Douala; Bamusso Ekondo Titi and Tiko-Limbe III in Southwest Region. Over 42.75% of mangrove forests are currently under this form of management with over 35% under communal forestry and 7.5% under community forestry regime (Table 21.5).

21.6.6 Research and Monitoring

Research is being undertaken in the expanse of Cameroonian mangroves by the joint efforts from universities, NGOs, and research institutes under different projects, especially those that have defined monitoring aspects to address conservation, sustainable utilization, and restoration of mangrove forests (Blasco et al. 2000; Longonje 2008; Ajonina et al. 2009a, b; CAMECO 2010; Nfotabong et al. 2011; Priso et al. 2011; Munji et al. 2013, 2014; Tening et al. 2014; Din et al. 2016). The Cameroon estuary block has benefited from many studies (Din 1991; Din et al. 1997, 2001, 2002, 2006, 2008; Ajonina and Usongo 2001; Asaah et al. 2006; Ajonina

Table 21.5 Mangrove communal and Community forests in Cameroon

Mangrove block	Ownership	Year of creation	Surface area (ha)	Mangrove (ha)	Sea (ha)	Mangrove (%)	As % National mangroves	Intervening partners
Communal (council) forests								
Rio Del Rey estuary	Idabato council	Ongoing	17,840	15,840	2000	88.79	7.16	GEF/MINEPDED partners
	Kombo Itindi	Ongoing	6265	6011	254	95.95	2.72	GEF/MINEPDED partners
	Ekondo Titi/Bamousso	2014	43,512	35,829	7683	82.34	16.20	GEF/MINEPDED partners
	Subtotal		67,617	57,680	9937	85.30	26.08	
Cameroon estuary	Tiko-Limbe III	Ongoing	34,561	20,170	3736	58.36	9.12	CWCS/PNDP/ MINEDEP
Ntem estuary			–	–	–	0	0	
Total under communal ownership			102,178	77,850	13,673	76.19	35.20	
Community forests								
Rio Del Rey estuary	Isangele	Ongoing	1698	1430	268	84.22	0.65	GEF/MINEPDED partners
	Kombo Abedimo and Idabato	Ongoing	3344	3250	94	97.18	1.47	GEF/MINEPDED partners
	Kombo Itindi (1)	Ongoing	3508	3400	108	96.92	1.54	GEF/MINEPDED partners
	Kombo Itindi (2)	Ongoing	3654	3560	94	97.43	1.61	GEF/MINEPDED partners
	Subtotal		12,204	11,640	564	95.38	5.26	
Cameroon estuary	Bimbia/Bonadikombo	2000	1921	52	14	2.71	0.02	BBNRMC/MINEF
	Manoka	2017	3195	2700	495	84.51	1.22	CAMECO/ MINFOF

	Dibamba	Ongoing	2530	2300	230	90.91	1.04	CAMECO/ MINFOF
	Subtotal		7646	5052	739	66.07	2.28	
Ntem estuary			–	–	–	0	0	
Total under community ownership			19,850	16,692	1303	84.09	7.55	
Grand total under participatory management			122,028	94,542	14,976	77.48	4.75	

2008; Din and Baltzer 2008; CAMECO 2010; Priso et al. 2011, 2012; Nfotabong et al. 2013; Tening et al. 2013; Ngo-Massou et al. 2014; Tchakonté et al. 2014; Fonge et al. 2015; Fusi et al. 2016; Tchinda et al. 2019; Besack et al. 2021; Kottè-Mapoko et al. 2021); although very few in the Ntem estuary block (Dika 2010; Nfotabong et al. 2011; Angoni et al. 2015; Moudingo et al. 2020; Mama et al. 2021).

Research addressing mangrove and wetlands management issues has also been done through the dissertations of students in universities, as various knowledge products including technical reports and scientific publications though with little communication to influence policy outcomes to protect mangrove forests and integration with indigenous knowledge systems. Moreover, research endeavors in mangrove and wetlands still suffer from weak technical, material, and operational capacities of most institutions coupled with addressing the question of sustainability of data collection activities where communities are involved in data collection efforts.

21.7 Perspectives for Sustainable Mangrove Management

21.7.1 Conclusions

Cameroon features among the countries in Africa with mangrove cover having a great structural peculiarity with diverse flora and fauna being the most giant in Africa and among the biggest and tallest in the world reaching over 1 m in diameter and 60 m in height especially around the Wouri estuary. The mangrove forests provide a wide range of vital ecosystem services which include: tangible ecosystem services (provisioning services) or natural resources as a means of subsistence for more than 30% of the population of the country living in coastal areas dependent on its resources, particularly wood and non-timber products including fishery products; non-tangible services including: regulatory services ranging from stabilization of the coastal zone, carbon sequestration to improvement of the micro- and macro-climate; support services, supporting the food chain, spawning ground and habitat for many other marine and aquatic animals; and cultural services as a venue for spiritual activities of festivals with enormous potential for ecotourism and environmental education. Mangrove and associated coastal areas have been lost annually at more than 1% in Cameroon though varying between regions. The driving factors are coastal population growth, urbanization, fish processing, sand extraction, and uncoordinated policies and government economic coastal development programs including accentuated pollution from extractive and processing industries. Government and partners contributed significant efforts through conservation (national parks and Ramsar sites) and sustainable management practices (communal and community forest regimes). Many awareness campaigns, sustainable utilization and restoration, and research initiatives have also been embarked upon. What really remains is the enhancement of management effectiveness of Cameroon mangroves through policy amelioration and coordinated efforts of the different stakeholders in the perspectives of sustainable management. Recommendations are therefore made to attain this goal.

21.7.2 Recommendations

Recommendations are made towards better conservation, sustainable use, and restoration of mangrove ecosystems and associated coastal forests through a win–win approach using whatever method/technique used (conservation, sustainable use, and restoration). There are five management approaches: holistic approach (multidisciplinary) involving different areas in the analysis of problems; ecosystem approach (man considered a component or link in the nature of chain); integrated approach (incorporating all relevant human activities: fishing, farming, hunting, farming, etc.); landscape approach (encourage connectivity of different ecosystems in the landscape); and participatory approach (development of partnerships with stakeholders, institutions, etc. involved).

The roles of different actors including government, NGOs, private sector, local communities and universities and research institute in implementing recommendations are equally discussed.

21.7.2.1 General Recommendations

Awareness Raising More awareness raising at all levels on mangrove ecosystems, its values and risks of its loss to trigger its integration and mainstreaming in all developmental planning processes at local, sub-national, and national levels.

Conservation Proper articulation of mangrove objectives and action plans in coastal and marine protected area systems including Ramsar sites.

Organizational and Functional Framework for Mangrove Stakeholders At the level of producers (fishermen and performers of related trades, woodcutters, sand farmers, etc.), co-management actions should aim at the organization of producers, coordination, harmonization of interventions, contribution to the rehabilitation of degraded areas, sharing of common benefits, etc. This development can build on institutions that are already functioning while working as needed on the creation of new institutions.

More Control and Monitoring of Mangrove Activities This includes mangrove timber cutting and marketing sector, in particular on local markets or in fishing camps; backed by proper regulations on the main activities undertaken in sensitive areas of mangroves.

Promotion of Good Management Practices Drawn from traditional know-how, including at the level of the promotion of achievements linked to local organizations of the populations.

Community-Based Mangrove Exploitation and Restoration Plans There is a need to promote and encourage the development and implementation of participatory plans for the exploitation and restoration of mangrove resources aimed at sustainable use within the municipalities with all the actors concerned.

Support Research Support research on all aspects that will lead to conservation, sustainable utilization, and restoration of mangrove ecosystems. Setting up a comprehensive database system on mangroves based on simple and accessible ecological, socio-economic, and institutional indicators to facilitate monitoring and reporting on mangrove utilization (wood, sand, fisheries, other natural resources) and ecosystems recovery/restoration dynamics and invasive alien species.

Funding Mechanism Exploration of funding mechanisms at different levels including adhesion to global initiatives especially carbon financing, 30 by 30, etc. to support conservation, sustainable utilization, and restoration initiatives within the mangrove ecosystems.

21.7.2.2 Recommendations on Legal Aspects

Legal Reforms Support the process of revising the 1994 forests, wildlife, and fisheries legislation as well as the 1996 framework law on the environment and their implementation texts to integrate, among others, considerations relating to the protection and sustainable management of the mangrove ecosystem in Cameroon. Mangrove be accorded a priority articulation of objectives, directives, and orientations for conservation, sustainable utilization, and restoration of mangrove ecosystems.

Appropriate Implementation of International Instruments Ensure the concrete and appropriate implementation of international instruments relating to elements of the marine and coastal environment to which Cameroon is a party.

EIA Legislation Strengthen the application of the framework law with regard to the realization of environmental impact studies for any project or important structure likely to affect the ecological balance of the mangrove area and help MINEPDED to mobilize resources for impact studies or other forms of studies carried out in mangroves relating to activities such as sand exploitation, logging, etc., reserved for the poor section of the population, in order to channel action operators instead of being confronted (by wanting to respect the precautionary principle) with a prohibition that is difficult to ensure. Need to set up and support the operation of a body responsible for ensuring the conduct of environmental impact studies and the implementation of mitigation or mitigation measures for the negative impacts identified.

21.7.2.3 Recommendations on Institutional Aspects

Proper Communications Strategies Within Existing Platforms Set up within collaboration platforms, communication strategies to avoid conflicts of competence/jurisdiction between different administrations. Building the intervention capacities of public services and other organizations involved in mangrove management.

Develop a Cross-Border Strategy Adapted to Mangroves This should aim, among other things, to channel the activities of other nationals in mangrove areas. Concerning issues relating to consultations (consultation frameworks and concerted actions), develop co-management initiatives and cross-border initiatives with Nigeria for the Rio Del Rey area and with Equatorial Guinea for the Rio Ntem area.

Coordination of Consultation Frameworks in Mangrove Ecosystems Several initiatives have been proposed (National Mangrove Committee, National Ecosystem Safeguarding Council, Sectorial mangrove management program, Cameroonian mangrove network, Various platforms, etc.). The Cameroon Mangrove network appears to be the most appropriate framework for collaboration for NGOs and grassroots organizations across all of Cameroon's mangroves. Target the intervention of administrations and other consultation bodies on specific actions in specific areas.

Participatory Monitoring Need to set up, with the participation of local populations, local mangrove harvesting monitoring committees in order to help resolve the problem of the inadequacy of public officials in charge of control and monitoring of management.

Private Sector Participation Encourage private sector participation in the mangrove management process as a potential sustainable funder of environmental actions and damage through payment for ecosystems schemes by enhancing the existing cooperative social and environmental policies already formulated by certain enterprises.

21.7.2.4 Roles of Stakeholders in Implementing Recommendations

Government Given the important cross-cutting role of mangroves in livelihood and ecological securities of coastal populations, the government through the various sectoral ministries (Agriculture, Forests, Wildlife, Fisheries, Livestock, Environment, etc.) should play a major regulatory role for the different sectors in a way that is compatible with the specificities of the mangrove ecosystem. This through the participatory process of developing and implementing good policies and practices leading to better conservation, sustainable use, and restoration of the mangrove ecosystem.

Non-governmental Organizations NGOs (local, national, and international) are already playing an important role in the proximity of mangrove communities; carrying out awareness-raising activities, environmental education, capacity building; and the implementation of development projects. Despite constraints and difficulties in accessing funding, it is necessary to continue to play this role.

Private Sector The private sector is very important not only as drivers of change, conversion, and degradation of mangroves through their activities, but also as a potential source of funding for improving impacts and the establishment of development projects to support local communities. The private sector can see themselves as small, medium, and multinational corporations (extractive industries: agro-industries, etc.).

Communities Riparian communities in the form of villages, decentralized local communities (local and urban councils) are always the recipients of negative or positive impacts from other actors. They must be the guarantors of mangrove ecosystems to which policies and good practices should benefit them.

Universities and Research Institutes In terms of formal training universities and research institutes play an important role in science and technology aimed at improving techniques for the conservation, sustainable use, and restoration of mangrove ecosystems by determining the potential (distribution map of species, stock, biodiversity, etc.), limits and techniques for the sustainable exploitation of mangrove resources.

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