3.5. Importance of Mangrove Ecosystem

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Mangrove forests are extremely important coastal resources, which are vital to our socio-economic development. A vast majority of human population lives in coastal area, and most communities depend on local resources for their livelihood. The mangroves are sources of highly valued commercial products and fishery resources and also as sites for developing a burgeoning eco-tourism (Kathiresan and Bingham, 2001). The mangrove forests have been shown to sustain more than 70 direct human activities, ranging from fuel-wood collection to fisheries (Dixon, 1989; Lucy, 2006). The mangrove ecosystem values to society estimated around the world is given in the table.1

Table 1. Various estimates for values of mangroves

Country	Item of value	Cost (US$/ha/year)	Author , year
Indonesia	traditional use	3,000 (half of income among the poorest households)	Ruitenbeek, 1992
Thailand	traditional use	230-1200	Christensen, 1982; Sathirathai, 1998
Southern parts of Thailand	traditional use	1,500 per household (a quarter of per capita GDP)	Sathirathai, 1998
In southern Thailand,	coastline protection and stabilization services	3,000	Sathirathai, 1998
	carbon sequestration	100	Sathirathai, 1998
Koh Kong Province in Cambodia	local level uses and indirect values	500-1,600	Bann, 1997
Rekawa, Sri Lanka	Coastal protection from storm and	1,000	Gunawardena and Rowan, 2005

	fisheries values		
Sri Lanka	storm protection	8,000,00	Batagoda, 2003

Irian Jaya	erosion control service	600 per household per year	Ruitenbeek, 1992
South of Vietnam	protection against extreme weather events	5,000,00	Tri *et al*., 1998
South east Thailand	Ecosystem function	10,000	Panapitukkul *et al*., l998
Global mangroves	forestry and fisheries benefits	500 - 2,500	Dixon, 1989
-do-	Disturbance regulation	1839	Costanza *et al*., l997
-do-	Waste treatment	6696	Costanza *et al*., l997
-do-	Habitat/refugee	169	Costanza *et al*., l997
-do-	Food production	466	Costanza *et al*., l997
-do-	Raw materials	162	Costanza *et al*., l997
-do-	Recreation	658	Costanza *et al*., l997
-do-	Total benefits	3294	Costanza *et al*., l997

Economic Benefits

The mangroves supply forestry products (firewood, charcoal, timber, honey *etc*.) and fishery products (fish, prawn, crab, mollusk *etc*.). Due to high calorific values, mangrove twigs are used for making charcoal and firewood. One ton of mangrove firewood is equivalent to 5 tons of Indian coal, and it burns producing high heat without generating smoke. The mangrove wood with high content of tannin is used as timber for its durability. The pneumatophores are used to make bottle stoppers and floats. *Nypa* leaves are used to thatch roofs, mats and baskets. Shells of mangrove molluscs are used to manufacture lime.

Mangroves attract honey bees and facilitate apiculture activities in some areas. For instance, the Sundarbans provide employment to 2000 people engaged in extracting 111 tons of honey annually and this accounts for about 90% of honey production among the mangroves of India (Krishnamurthy, l990). In Bangladesh, an estimated 185 tons of honey and 44.4 tons of wax are harvested each year in the western part of the mangrove forest (Siddiqi, l997). The best quality honey is produced from *Aegialitis rotundifolia* and *Cynometra ramiflora.* The bulk of honey seems to come from *Ceriops.*

Mangroves and especially *Avicennia* form cheap and nutritive feed for buffaloes, sheep, goats and camels. These animals are allowed to graze in mangrove areas and camels are periodically taken to uninhabited islands with a good mangrove cover for grazing. This is very common in India, Pakistan, Persian Gulf region and Indonesia (Qasim, l998). To cite an example, about 16,000 camels are herded into the mangroves of Indus delta of Pakistan (Vannucci, 2002).

Mangrove extracts are used in indigenous medicine; for example, *Bruguiera* species (leaves) are used for reducing blood pressures and *Excoecaria agallocha* for the treatment of leprosy and epilepsy. Roots and stems of *Derris trifoliata* are used for narcotizing fishes, whereas *Acanthus ilicifolius* is used in the treatment of rheumatic disorders. Seeds of *Xylocarpus* species have antidiarrhoeal properties and *Avicennia* species have tonic effect, whereas *Ceriops* produce hemostatic activity. Barks of *Rhizophora* species have astringent, antidiarrhoea and antemetic activities. Tender leaves of *Acrostichum* are used as a vegetable and a beverage is prepared from the fruits of *Sonneratia* spp. Extracts from mangroves seem to have a potential for human, animal and plant pathogens and for the treatment of incurable viral diseases like AIDS (Kathiresan, 2000).

The mangroves provide seeds for aquaculture industries. To cite an example, 40,000 fishers get an annual yield of about 540 million seeds of *Penaeus monodon* for aquaculture, in the Sundarban mangroves of West Bengal (Chaudhuri and Choudhury, 1994). One hectare of mangroves can yield 767 kg of wild fish and crustaceans, which is more than the yield in extensive system that can yield <500 kg ha^{-1} yr^{-1}. Each hectare of a managed mangrove system produces as much as $ 11,300 a year at par with an intensive shrimp farming (Primavera, 1991). Apart from these direct products, the mangrove ecosystems provide a number of ecological services.

Ecological Services

Much of the ecological service of mangroves lies in protecting the coast from solar UV-B radiation, 'green house' effects, and fury of cyclones, floods, sea level rise, wave action and coastal erosion. Mangrove swamps act as traps for the sediments, and sink for the nutrients. The root systems of the plants keep the substrate firm, and thus contribute to a lasting stability of the coast. The ecosystem provides a source of food, breeding grounds and nurseries for many food fishes and shellfishes, and they do very often encourage and attract other kinds of wildlife. They further help in offering protection to other associated flora and fauna of the ecosystems including the islands. The mangrove ecosystems are highly productive and comparable to good agricultural land. Benefits of mangroves are 25 fold higher than that of paddy cultivation.

Screening the solar UV-B radiation

Mangroves possess mechanisms to deal with intense sunlight rays and solar UV-B radiation. For example, *Avicennia* species grow in areas endowed with high sunlight, hot and dry conditions and the species are well adapted to arid zones. Rhizophoracean species show greater solar UV-B tolerance than do other mangrove species. The mangrove foliage produces flavonoids that serve as UV-screen compounds. This ability of mangroves makes the environment free from the deleterious effects of UV-B radiation (Moorthy & Kathiresan, l997 a,b).

Reducing the 'green house effects'

Mangroves are known to remove CO_2 from the atmosphere through photosynthesis. This perhaps reduces the problems that go with the 'green house gases' and global warming. They fix greater amounts of CO_2 per unit area, than what the phytoplankton do in the tropical oceans (Kathiresan & Bingham, 2001). The mangroves are capable of accumulating and storing carbon in the soil in large quantities. For example, the ability of *Rhizophora* forest to divert carbon belowground is remarkably high. A 20-year old plantation of mangroves stores 11.6 kg m^{-2} of carbon with C burial rate of 580 g m^{-2} yr^{-1} (Fujimoto, 2000) and hence, plantation of mangroves provides great benefits to control global climate change by stabilizing atmospheric carbon. Mangroves also respond well to high CO_2. For example, *Rhizophora mangle* under high CO_2 conditions which was double than normal for one year, showed greater accumulation of biomass (Farnsworth *et al.*, 1996). Because the mangroves fix and store significant amounts of carbon, their loss may have impact on global carbon budget. Cebrain (2002) estimated that a loss of about 35% of the world's mangroves has resulted in a net loss of 3.8×10^{14}g C stored as mangrove biomass.

Minimizing the fury of cyclones

Mangrove forests protect all types of coastal communities from the fury of cyclones and storms. The best example on finds is the super-cyclone which occurred on the 29th October 1999 with a wind speed of 310 km hr^{-1} along the Orissa coast (India) and played havoc largely in the areas devoid of mangroves. On the contrary, practically no damage occurred in regions with luxuriant mangrove growth. Similarly, in the Mahanadi delta, where large-scale deforestation and reclamation of mangrove land for other purposes have been undertaken, maximum losses of life and property have been reported from time to time during stormy weather. These events beyond doubt prove that mangroves can form the best shelterbelt against cyclones and storms and have generated awareness among the local communities of the importance of mangrove forests as protectors of life and property.

There are several other examples on record to be cited. For instance, the l970 typhoon and the accompanying tidal waves that claimed about 3 lakh human lives in Bangladesh probably would not have been so devastative if thousands of hectares of mangrove swamps would not have been cleared and replaced with paddy fields for short-term economic gains. Likewise, in the Kachchh areas of Gujarat, where mangrove trees were illegally cut the effect of the heavy cyclone during l983 was felt deep inside the human habitation, which took a heavy toll of lives.

Tropical cyclones and storms are more common in the Bay of Bengal. They thus severely affect the south Indian coast as compared to that of the Arabian Sea. According to Koteswaram (l984), there were about 346 cyclones that include 133 severe ones in the Bay of Bengal, whereas the Arabian Sea had only 98 cyclones including 55 severe ones between the years l891 and l970. These cyclones with tremendous speed hit the coastline and inundate the shores with strong tidal wave, severely destroying and disturbing coastal life. However, mangroves like *Rhizophora* spp. seem to act as a protective force towards this natural calamity (McCoy *et al.,* 1996).

Mitigating the fury of tsunami

After World War II, if there was another tragedy in human history, it was indeed the tsunami of December 26, 2004 that killed 3 million people in Asian and African countries, made about 2 million people homeless and that resulted in a loss of 6 billion US $ in 13 countries (Kathiresan and Rajendran, 2005). The tsunami-waves were generated due to an under-sea earthquake, measured at 9.3 on the Richter scale, the world’s largest earthquake after the

Alaskan event of l964. In India, the monstrous waves devastated Andaman and Nicobar Islands and southeast coast of the country, but spared the areas that are colonized with luxuriant mangroves. Covering an area of 4,461 km^2, the mangrove forests in India is rich in biodiversity with 3,943 biological species that include 71 mangrove species, of which 21 are of rare occurrence and only one species, *Rhizophora annamalayana* Kathir., is endemic to India (Kathiresan and Bingham, 2001). This paper deals with the role of mangroves in coastal protection against tsunami with a case study from India.

I am an eye-witness of the tsunami and its energy dissipation by mangroves that saved our lives and laboratory, lying behind the mangrove forest. A boat jetty was broken into pieces, while the mangrove forest adjoining to it was not disturbed (Fig. 1). Hence, an assessment was undertaken after the tsunami in 18 coastal villages (Lat. 11°26-30′ N; Long. 79°45-48′ E) existing in about 25-km stretch along the southeast coast of India. The locations of villages range between 0.1 and 2.5 km away from the shore, and their elevations vary between 0.5 and 4 m from mean sea level. The study area has two mangrove formations: one is naturally formed at Pichavaram with an area of 11 sq. km; and, another one is 15-year old, developed artificially by author of this paper. Data on loss of human lives and wealth of the villages were collected along with coastal vegetation and human inhabitation characteristics, as shown in the Table 1 (Kathiresan and Rajendran, 2005).

Loss of human lives ranged from 0 to 110 for every 1000 persons of the study area. Of death cases, women occupy 53%, followed by children (27%) and men (20%). A heavy loss of human lives was recorded in six villages (No. 17 – 110 deaths, No. 11 – 96, No. 16 – 80, No. 3 – 72, No. 9 -55 and No. 13 – 55; Table 2). These villages are in close proximity to the shoreline between 0.1 and 0.4 km without any vegetation cover, and they are also in low-lying sandy shore area with smooth topography. This situation facilitated tsunami-waves to rush into the human inhabitation and caused havoc with a total loss of US $ 3.482 million. The per capita loss of wealth in different villages ranged from US $ 9 to US $ 1000 exhibiting a trend, similar to human death.

The human death was nil in three villages (No. 7, 8 and 14) and low in four villages (No. 10 – 4 deaths, No. 18 – 5, No. 15 – 10 and No. 12 – 11 deaths; Table 2). All these villages (except No. 8 and 10) are situated behind the mangrove forests, located at a distance ranging from 1 to 2.5 km away from the shoreline and also are in elevated places with steep topography. This situation reduced the speed of the tsunami waves, resulting in negligible loss of human lives. The villages (No. 8 and 10) are located in close proximity of less than 1 km distance from the sea, however they did not loose much human lives, for the reason that they are situated in elevated shore area, protected with a dense vegetation of casuarinas, Palmyra and coconut trees in the sand dunes.

This study concludes that the tsunami-induced human death and property loss were less behind mangroves and sand dunes. The mortality reduced with increasing elevation of human inhabitation above mean sea level, whereas property loss got reduced by distance to the shore (Fig. 3).

Tsunami mitigation by mangroves and sand dunes has been proved using satellite data in the same study area (Danielsen *et al*., 2005). The dense growth of mangroves in Sundarbans saved West Bengal in India and Bangladesh from the killer impact of tsunami. Myanmar and Maldives suffered very less from the tsunami; one of the reasons for which was the tourism industry had so far not spread to the virgin mangroves surrounding the coastline. In Thailand, mangroves that surround the Island of Surin off the west coast helped to break the lethal power of the tsunami. Two villages in the lagoon of southern Sri Lanka showed the importance of mangroves in saving lives: in Kapuhenwala, surrounded by 200 hectares of dense mangroves and scrub forest, the tsunami killed only two people, whereas Wanduruppa, surrounded by degraded mangroves was severely affected with 6,000 death cases (IUCN, 2005; http://www.iucn.org/tsunami).

There were a few instances of very large tsunamis which occurred beyond the capacity of mangroves and other vegetation to offer coastal protection. In Indonesia, Banda Aceh coastline received no protection from natural ecosystems, against the tsunami wave height of 30 m. Another example is the tsunami of Krakatoa of Indonesia in 1883 with a wave height of 35 m that penetrated up to 8 km inland through primary rainforest (Tsunami Risks Project, 2005). In the Nicobar Islands, mangroves were victims of the 2004-tsunami with wave height of 7 m, penetrated up to 1 km inland. Young saplings were removed completely and some of the larger trees were also uprooted there. The extent of damage for mangrove cover in the Nicobar Islands ranged from 51 to 100% - 339.03 ha (69%) in Katchal, 335.7 ha (51%) in Camorta, 240.06 ha (68%) in Trinkat, and 152.53 ha (100%) in Nancowry (Ramachandran *et al*., 2005). In Andamans, the tsunami with wave height of 3.9 m caused considerable change in the mangrove stands of the islands; where, *Avicennia marina* and *Sonneratia alba* were not generally affected, while in some places, *Rhizophora* species got affected due to continuous submergence by seawater due to tsunami waves. In South Andaman, 30-80% of mangrove stands got affected in four localities (Sipighat junction – 80%, Minnie bay -40%, Chouldari-30% and Wandoor -30%); however, in middle Andaman and North Andaman, mangroves were not affected due to elevation of land. The tidal waves damaged mangrove-associate species, *Acrostichum aureum* and *Fimbristylis littoralis*. Immediately after the tsunami, mortality of shellfishes such as prawns and crabs was observed in the vicinity of mangrove areas due to leaching of acid sulphate salts and water quality deterioration (Dam Roy and Krishnan, 2005). The tsunami also destroyed seaweed habitats in South Andaman due to damage to mangrove vegetation. Regeneration of the habitat-specific seaweed populations depends on the restoration of mangrove plants (Mantri, 2005).

The mitigating effect of mangroves depends on their response to two physical processes of tsunami - (i) wave attack, and (ii) towing flow. Mangrove's response to wave attacks depends on its vegetation characteristics, whereas the response to towing flow relies on 'drag force' caused by the mangroves, resulting in prevention of coastal erosion. Thus the protective role of mangroves depends on: (i) vegetation characteristics such as, density, height, species composition, density of forest, diameter of mangrove roots and trunks, and elevation of habitats, as well as status of ecological degradation of the forests; and, (ii) tsunami wave characteristics such as, wave height, wave period, depth of water (Mazda *et al*., l997a,b).

The role of mangroves in reducing the sea-waves is scientifically proved. Harada *et al.* (2002) have conducted a hydraulic experiment to study the tsunami reduction effect of the coastal permeable structures using five different models - mangroves, coastal forest, wave dissipating block, breakwater rock, and houses. This work reveals that mangroves are effective as compared to concrete seawall structures for reduction of tsunami-hit house damages behind the forest. Mazda *et al*., (l997a) have reported that six-year-old mangrove forests of 1.5 km width reduce the sea-waves by 20 times, from 1 m high waves at the open sea to 0.05 m at the coast. The reduction of wave amplitude and energy by tree vegetation has also been proved by measurements of wave forces and modeling of fluid dynamics (Massel *et al*., l999). Analytical model shows that 30 trees from 10 m^2 in a 100-m wide belt may reduce the maximum tsunami flow pressure by more than 90 %, if the wave height is less than 4-5 m (Hiraishi and Harada, 2003). In the present study area, the tsunami wave height was only 2.8 m and the mangrove forest height was about 3-5 m, with a density of 25 trees/10 m^2. In my opinion, the mangroves would provide protection against tsunami in the situation, where the height of mangrove forest (with >25 trees/10 m^2) is higher than that of tsunami wave height. Protection and restoration of mangroves, coastal forests and sand dunes would mitigate the impacts of not only tsunamis, but also storms and sea level rise.

Table 2. Impact of tsunami on loss of human lives and wealth in 18 different fishermen villages existing along south east coast of India

Fishermen village No.	Human inhabitation		Coastal vegetation		No. of Deaths*					Per capita Loss of Wealth (huts, gears & crafts (US$)
	Distance from sea (Km)	Elevation from mean sea level (m)	Nature of Habitat	Area (ha)	Male	Female	Child	Total	No./1000 individuals	
1	0.3	2.0	Sandy shore with mid shore dunes	0. 5	2	4	1	7	16	511
2	0.3	3.0	Sandy shore with mid shore dunes	0.9	2	20	3	25	12	244
3	0.4	0.8	Low-lying sandy shore with embryonic dunes	0.1	23	57	13	93	72	333
4	0.4	2.0	Sandy with mid shore dunes	0.3	8	24	11	43	24	267
5	0.7	1.0	Sandy shore with hind dunes	0.4	9	17	2	28	19	244
6	0.7	3.3	Sandy shore with mid shore dunes	0.15	4	7	1	12	14	444
7	2.0	2.0	Muddy shore with dense mangroves	10	No death (0) No death (0)				0	18
8	1.0	4.0	Elevated sandy shore with hind dunes	11.3					0	378
9	0.2	0.5	Low lying sandy shore with embryonic dune	0.52	1	3	5	9	55	1000
10	0.4	4.0	Elevated steep sandy shore with mid shore dunes	15	1	1	0	2	4	289
11	0.1	0.8	Low lying sandy shore	0.2	8	21	26	55	96	956
12	1.0	1.0	Mud-sandy shore with shrubby mangroves	2.0	2	2	1	5	11	222
13	0.1	0.5	Low lying sandy shore	0.8	1	6	4	11	55	489

14	2.5	2	Muddy shore with dense mangroves	10	No death (0)				0	44
15	2.5	1	Muddy shore with dense mangroves	2	2	2	1	5	10	44
16	0.15	0.5	Low lying sandy shore	0.28	0	1	3	4	80	267
17	0.15	0.5	Low lying sandy shore	0.08	2	5	12	19	110	178
18	2.0	1.0	Muddy shore with dense mangroves	10	1	1	3	5	5	9

Fig.1. Showing a boat jetty across the Vellar estuary (south-east coast of India) broken into pieces by 26th December 2004 tsunami along with intact mangrove forest, raised artificially

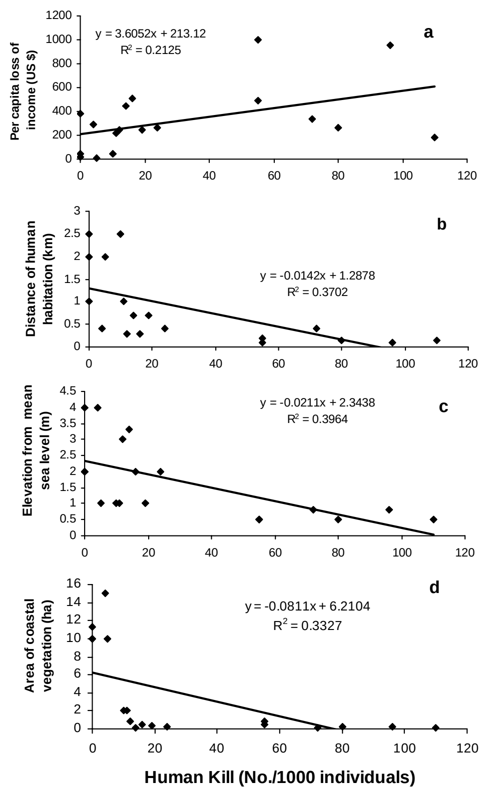

Fig. 2. Human kill after tsunami of 26th December 2004, in relation to per capita property loss, distance and elevation of human inhabitation and area of coastal mangrove vegetation

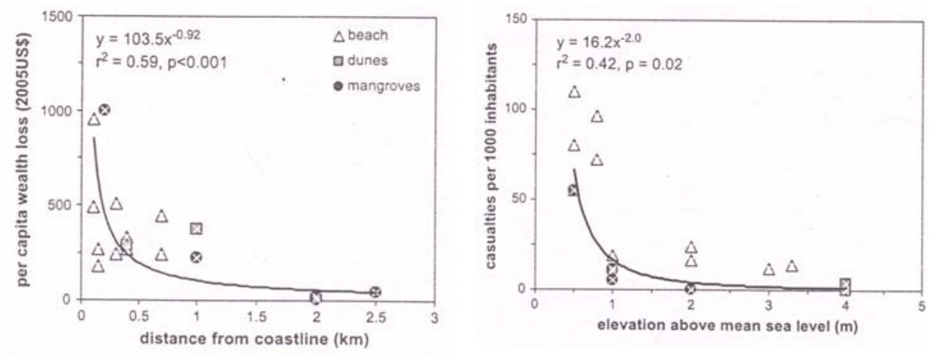

Fig. 3. The human death and wealth loss in response to distance from coastline and elevation above mean sea level (Vermaat and Thampanya, 2006, based on data of Kathiresan and Rajendran, 2005).

Controlling the flood

Mangrove systems offer protection to the coastline against the flood, which are often caused by tidal waves or due to heavy rainfall associated with storms. The serious flood disaster of l991 in Bangladesh would certainly have minimized, had the 300 km^2 mangrove area not been cleared for shrimp farming and rice cultivation earlier. The ability of mangroves in flood control is due to the response of their root system to have a larger spread out in areas prone to tidal inundation, and their roots to promote sedimentation.

Besides flood control, the mangroves prevent the entry of seawater inland and thus protecting the underground water systems, forming a source of drinking water supply to coastal population. Very often very sharp changes have been noticed in salt concentrations of groundwater at the interface between salt flats and mangroves. This suggests that the mangrove systems can modify the salinity of the groundwater by lowering it drastically (Ridd & Sam, l996).

Prevention of the coastal erosion

The mangrove systems minimise the action of waves and thus prevent the coast from erosion. The reduction of waves increases with the density of vegetation and the depth of water. This has been demonstrated in Vietnam. In the tall mangrove forests, the rate of wave reduction per 100 m is as large as 20% (Mazda *et al.*, l997). Another work has proved that mangroves form 'live seawalls', and are very cost effective as compared to the concrete seawall and other structures for the protection of coastal erosion (Harada *et al*., 2002).

The mangrove forest of 100 m width protected the sea dyke, lying behind the forest, for more than 50 years. In contrast, the rock fencing protected the sea dyke for only about five years. This is because of the fact that the rock fencing is not long resistant to wave damage, as compared to mangrove forest, as proved in the Red River Delta, Vietnam. The planting of mangrove has cost of US$ 1.1 million but has helped reduce maintenance cost of the seadyke by US$ 7.3 million per year (World Disaster report, 2002). However, the deforestation of mangroves causes erosion problems, as has been noticed in the Gulf of Kachchh and other regions.

Trapping the sediments

One of the important functions of mangroves is trapping of sediment, and thus acting as sinks to the suspended sediments (Woodroffe, 1992; Wolanski *et al.,* 1992; Wolanski, 1995; Furukawa *et al.,* 1997). The mangrove trees catch sediments by their complex aerial root systems and thus function as land expanders. In numerous cases, there has been proof of annual sedimentation rate, ranging between 1 and 8 mm, in mangrove areas with expansion of land (Bird & Barson, l977). Woodroffe (l992) has a different view that the mangrove forests are the result, and not the cause of sedimentation in protected coastal areas, and that they accelerate the role of sedimentation process. This depends largely on the complexities involved in the exchange process taking place between mangroves and the adjoining coastal areas.

The mechanism of sediment trapping in mangrove habitats is shown in Fig. 2 (Furukawa *et al.,* 1997; Kathiresan, 2003a). The mangrove structures inhibit tidal flows, probably due to the friction force which the trees with their root system provide. The soil particles are carried in suspension into mangrove forests from seawater by the incoming tide, and the soil particles are left behind in the swamps and within the root system by the outgoing tides. Thus, the particles settle in the forests during the low tide, probably when the turbulence gets reduced and water velocity at low tide becomes sluggish and low to carry the particles back to the sea (Fig. 4). It has been estimated by Kathiresan (2003a) that mangroves help in trapping the sediment up to 25 % at low tide as compared to high tide. This high efficiency of trapping suspended sediment may be attributed to widespread occurrence of numerous respiratory roots in *Avicennia* and to compactly arching stilt roots of *Rhizophora.* The density of mangrove species and their complexity of root systems thus constitute most important factors, for determining the sedimentation process.

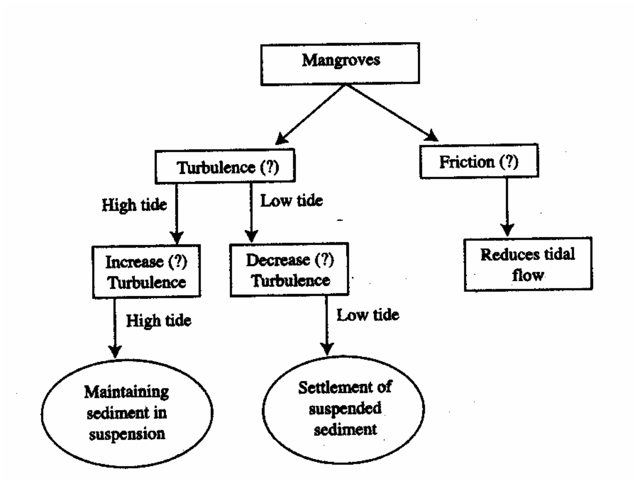

Fig. 4. Mechanism of sedimentation as induced by mangroves (From Kathiresan, 2003a)

The sedimentary process varies among the different types of mangrove forests namely riverine, basin and fringe types. The process falls in decreasing order: Riverine> basin> fringe (Ewel *et al.*, 1998). The river-dominated system receives an allochthonous sediment supply and the deposition of the quantity of sediment is a function of the catchment-size. The tide-dominated fringe system contains abundant allochthonous sediment, but the sedimentation gets disturbed by the tides. The interior basin mangroves form sinks for the sediments (Woodroffe, 1992).

Deepening the creeks

Water circulation through mangrove forests is important especially for the riverine forest, which often consists of tidal creeks and surrounding forest swamps. The water movement in the creeks is different from the swamps, as the former is deep, while the latter is shallow, colonized with vegetation. The cause of water movement is the tide. The flow of water during the low tide is much greater than that of the high tide (Fig. 3). For example, the riverine mangroves produce asymmetrical tidal currents which are 50% stronger at the low tide than at the high tide (Medeiros & Kjerfve, 1993). The fast low tide tends to flush out the material from the mangrove area and maintains the depth of creeks. If the area of forest swamp is reduced, then the speed of the low tide is reduced and there is a possibility for the creeks to get clogged up. This has been commonly observed in some Southeast Asian countries where deforestation of mangroves has reduced the navigability of the canals and river mouths (Wolanski *et al.,* l992).

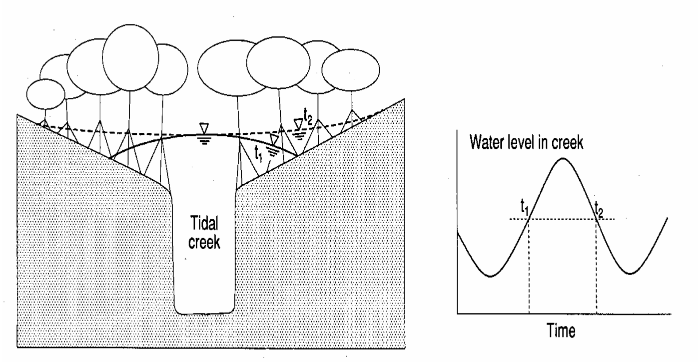

Fig. 5. The water level in the creek-mangrove forest system at low tide (time t_1 & t2 ; from Wolanski *et al.*, l992)

In the Fig. 5. the water levels in the creek mouth at low tide (time t_1) and high tide (time t_2) are the same. However, the water levels in the forest swamp are different. The low tide in the forest swamp occurs when the water level at the creek mouth is already falling and thus there is less time for the water to leave the system on the low tide. This results in stronger currents of low tide than high tidal currents (Wolanski *et al*., l992).

Trapping and recycling of nutrients

The mangrove sediments have the ability to retain nutrients. This depends on the sediment characteristics and flow patterns of the sites. For example, in severely damaged sites of North Queensland, there was a significant loss of nitrogen and phosphorus from the soil, because the flow of water was greatly reduced (Kaly *et al.,* l997). The mangrove systems also help in recycling of carbon, nitrogen and sulphur. It is perhaps the only biotic system that recycles sulphur efficiently in nature, and making it available in assimilable forms to other organisms.

Mangrove habitats have survived the onslaught of man by using them as sites for dumping of organic wastes. Their survival is because of three reasons: (1) flow through the habitat disperses wastes from a point source over vast areas, (2) the vegetation itself filters nutrients from the water, and (3) the mangrove soil, algae, microbes, and physical processes absorb large amounts of pollutants (Wong *et al*., 1995).

Mangroves such as *Avicennia* spp. in general are tolerant to high organic load. In Indonesia, *Avicennia* spp. and *Acanthus ilicifolius* are planted in aquaculture ponds for controlling salinity and *p*H in rainy season (Lacerda *et al*., 2002).

Mangrove sediments have a high capacity for absorbing and holding heavy metals thereby preventing the spread of metal pollution in coastal areas. The sediments contain 90% of Mn and Cu released and almost 100% of the Fe, Zn, Cr, Pb, Cd in the total ecosystem. However, mangrove species (*Rhizophora mangle*) contains less than 1% of the total of these metals (Silva *et al.,* 1990). This may be due to (1) low bioavailability in the mangal sediments, (2) exclusion of the metals by the mangrove plant itself, or (3) physiological adaptations that prevent accumulation of metals inside the plants. Oxygen exuded by the underground promotes the formation of iron plaques that adhere to the root surfaces and prevent trace metals from entering the root cells. The metals are precipitated in the form of stable metal sulphides under anoxic conditions, and this process decreases the bioavailability of unfavourable trace metals in the mangrove sediments. Trace metals like Hg, which do not form sulphides are immobilized in organic complexes in mangrove sediments. Disturbances may cause the mangrove soil to lose its metal binding capacity, resulting in to mobilisation of metals. The mangal then gradually shifts its site from a heavy metal sink to source where the accumulation is relatively low (Lacerda, 1998).

Supporting the fishes and wildlife populations

Mangrove ecosystems are important for fish production. They serve as nursery, feeding and breeding grounds for many fishes and shellfishes. Nearly 80% of the fish catches are directly or indirectly dependent on mangrove and other coastal ecosystems worldwide (Kjerfve & Macintosh, 1997). To cite a specific case, the Pichavaram mangroves alone nurture 30 species of prawns, 30 species of crabs, 20 species of mollusks, and 200 species of fish (Kathiresan, 2000b). It is widely believed that the mangroves are like the roots of the sea and, if there are no mangrove forests along the coast, there will be either no fish or fewer fish in the sea and the sea will act like a tree without roots. Besides fish, the mangroves support a variety of wildlife such as the Bengal tiger, crocodiles, deer, pigs, snakes, fishing cats, insects and birds.

The detached parts of the mangrove plants when fall on the floor are called 'litter-fall'. These include leaves, stems, roots, flowers and fruits. Microorganisms found in the soil decompose the fallen parts.

During this process, nutrients are released which enrich the surrounding waters. The decomposed organic matter along with microbial biomass is known as detritus. This is an important product produced in the mangrove ecosystems. It is rich in protein and it serves as a nutritious food for a variety of organisms. The organisms feed on detritus or filter the detritus-particles from the water column. Such detritus–feeding fishes are preyed upon by larger carnivorous forms. The influx of nutrients generated by the mangroves supports other sensitive habitats like the coral reefs, seaweeds and seagrass beds.

Detritus largely consists of both living and inert materials in suspension, which continuously settles to the bottom. Calorific value of detritus in the Zuari estuary, Goa ranged from 173 to 6057 cal g^{-1} dry weight (average 1463) which was much higher than that found in Cochin Backwaters where the range was 200–500 cal. g^{-1} dry weight (Qasim & Sankaranarayanan, 1972). This is because the detritus from Zuari contains substantial quantities of decaying mangrove leaves (Kumari *et al.*, 1978). The Mandovi-Zuari estuarine complex is a mangrove fringed ecosystem (1600 hectares of mangrove forest are spread all along the estuarine areas) with litter yield, ranging from 10.2 to 17.0 tonnes ha^{-1} yr^{-1} with a maximum fall in pre - and post-monsoon months and minimum during the monsoon season. Thus mangroves become a very important source for maintaining the carbon budget, sustaining microbial food chain and recycling of nutrients in the estuarine complex (Wafer *et al.*, 1997). The functional aspect of mangrove ecosystem is detailed here for better understanding.

Biomass and Litter Production

Mangroves contribute significantly to the global carbon cycle. Mangrove forest biomass may reach 700 t ha^{-1} (Clough, 1992) and Twilley *et al.* (1992) estimate the total global mangrove biomass to be approximately 8.7 gigatons dry weight (*i.e*. 4.0 gigatons of carbon).

Mangroves generally grow better in wet equatorial climates than they do in seasonally monsoonal or arid climates (Clough, 1992) and the amount of litter they produce is negatively correlated with latitude. Estimates of the annual global litter fall from mangroves range from 130 to 1870 g m^{-2}. In general, the litter fall is heaviest (1) in dry summer months when thinning of the canopy reduces transpiration, and (2) in the wet rainy season when fresh water input increases the nutrient supplies (Wafer *et al.*, 1997). However, individual species may differ in the conditions that produce heavy litter. For instance, Australian

Rhizophora stylosa and *Avicennia marina* show heaviest litterfall in hot climates with short dry seasons, but *Ceriops tagal* litterfall is heaviest in hot climates with long dry winter (Bunt, 1995). In India, *Avicennia marina* litter production is high in the post-monsoon period and low in the pre-monsoon season (Ghosh *et al.,* 1990). Deviations from these general patterns of litterfall may result from habitat-specific stresses (*e.g.* aridity, poor soils; Saenger and Snedaker, 1993).

A number of researchers have measured mangrove litter fall. Results show a broad range of litter volumes varying significantly from habitat to habitat. The production appears to depend largely on local conditions, species composition, and productivity of the individual mangal. Litter production has been variously measured at 0.011 t ha^{-1} yr^{-1} in the mangroves of Kenya, 9.4 t ha^{-1} yr^{-1} in Bermuda, and 23.69 t ha^{-1} yr^{-1} in Australia.

Litter from the mangroves is composed of leaves, twigs, branches and seeds. Seeds alone accounted for 25% of the total litterfall for *Avicennia germinans* and *Rhizophora mangle* in a mangrove habitat in Martinique (Imbert and Menard, 1997). In a temperate mangle, the reproductive material was approximately 9% of the total for *Avicennia marina* and 32% of the total for *Aegiceras corniculatum*. Clarke (1994) suggested that such relatively high reproductive output may contribute to the low productivity and stunting of mangroves at high latitude.

Accumulated mangrove litter may wash into rivers and streams when rain or tides inundate the forest. Consequently, mangrove litter may decompose either in the source forest or in the river, with nutrients being retained or exported (Conacher *et al.,* 1996). Whether the litter (and its nutrients) remain in the habitat or are exported by water flow may depend largely on the local animal community. On the east coast of Queensland, the litter accumulation in a *Ceriops* forest was 6 g m^{-2} (0.84 t ha^{-1}; Robertson *et al.,* 1992). This enormous difference in accumulation was attributed to the feeding activities of crabs.

Litter Decomposition and Nutrient Enrichment

Mangrove ecosystems produce large amounts of litter in the form of falling leaves, branches and other debris. Decomposition of the litter contributes to the production of dissolved organic matter (DOM) and the recycling of nutrients both in the mangal and in adjacent habitats. The organic detritus and nutrients could potentially enrich the coastal sea and, ultimately, support fishery resources. The contribution of the mangroves could be particularly important in clear tropical waters where nutrient concentrations are normally low.

The nutrient cycling begins when leaves fall from the mangroves and are subjected to a combination of leaching and microbial degradation (Lee *et al.,* 1990; Chale, 1993). Leaching alone removes a number of substances and can produce high levels of DOM (Benner *et al.,* 1990). Potassium is the most thoroughly leached element with up to 95% of the total potassium being removed in a very short time (Steinke *et al.,* 1993). Carbohydrates also leach quickly during early decomposition. Tannins, in contrast, leach very slowly and the high tannin contents may slow colonization of bacterial populations in the initial period of decomposition. As the tannins are eventually leached, and bacterial populations rapidly increase (Steinke *et al.,* 1990; Rajendran, 1997; Rajendran and Kathiresan, 1999b).

Bacteria and fungi contribute to decomposition of the mangrove material and to the transformation of cycling of nutrients. Fungi are the primary litter invaders, reaching their peak in the early phases of decomposition (Rajendran, 1997). The phylloplane fungi do not attack live leaves; they begin to break the leaf material down only after it has been submerged.

Bacterial colonies appear shortly after the litter has been colonized by fungi. The bacteria grow quickly and can reach very high densities. Zhuang and Lin (1993) measured bacterial densities from 2 x 10^5 to 10 x 10^5 g^{-1} on *Kandelia candel* leaves that decomposed for 2-4 weeks. This was about 100 times higher than densities of actinomycetes and filamentous fungi. The N_2-fixing azotobacters are one of the important groups in the decomposing litter (Rajendran, 1997) and their activities may increase the nitrogen content of the leaves 2-3 times (Rajendran, 1997; Wafar *et al.,* 1997).

Chale (1993) measured a similar rapid nitrogen increase in leaves after six weeks of decomposition and suggested that the litter (1) provides a surface for microbial nitrogen synthesis and (2) acts as a nitrogen reservoir. The C:N ratio of decomposing *Avicennia marina* leaves drops dramatically from approximately 1432 to 28, primarily as a result of a large increase in their nitrogen content (Mann and Steinke, 1992).

A number of factors can affect the rate of litter decomposition and, therefore, the rates of nutrient cycling. For example, litter decomposition rates vary among mangrove species. *Avicennia* leaves, because they are thinner and have fewer tannins, decompose faster than those of other species (Sivakumar and Kathiresan, 1990; Steinke *et al.*, 1990; Kristensen *et al.*, 1995). *Avicennia* leaves also sink and begin to decompose immediately whereas the leaves of other species (*e.g. Sonneratia* and *Rhizophora*) may float for several days (Wafar *et al.*, 1997). Lu and Lin (1990) found that litter of *Bruguiera sexangula* decomposes quickly. *Aegiceras corniculatum*, in contrast, decomposes slowly (Tam *et al.*, 1990).

Decomposition is influenced by tidal height, rainfall and temperature. In subtropical mangrove forests, mangrove debris decomposes substantially faster in the rainy season. Mackey and Smail (1996) studied decomposition of *Avicennia marina*. They found significantly faster decomposition in lower intertidal zones with greater inundation. They also found an exponential relationship between leaf decomposition rate and latitude with leaves decomposing most quickly at low latitudes. They attributed the pattern to temperature differences, and concluded that seasonality can have important effects on organic cycling and nutrient export from mangrove systems.

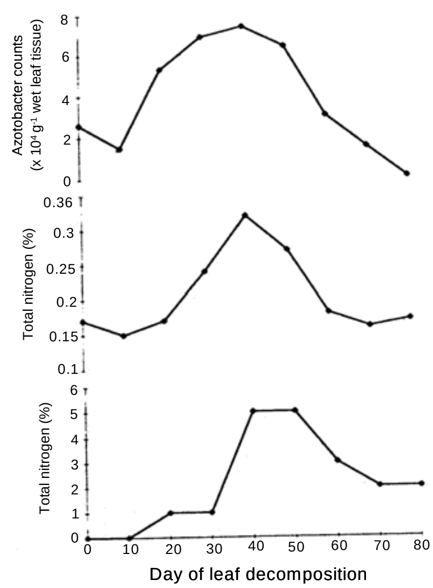

Fig.6. Changes in the nitrogen – fixing azotobacter counts ($1x10^4$ g^{-1} leaf tissue), the total nitrogen content (% of leaf tissue) and the juvenile prawns (no. $haul^{-1}$) associated with decomposing senescent leaves of *Avicennia marina*, kept in nylon bags (35 cm x 35 cm. 2mm mesh size) and submerged in mangrove waters at Pichavaram. During July-September, 1996. (Source: Rajendran, 1997).

Breakdown and decomposition of mangrove litter is accelerated by the feeding activities of invertebrates (Camilleri, 1992). The animals may process large volumes of the litter, contributing significantly to nutrient dynamics. Litter turnover rates have been estimated by measuring rates of leaf decomposition. However, estimates made this way are generally 10-20 times lower than rates calculated from actual measurements of leaf fall and litter standing crop. The differences in the estimates can be attributed to (1) tidal export and (2) the feeding activities of crabs. Crab feeding may be the more important of these in many regions. For example, in the Ao Nam Bor mangrove forest in Thailand, crabs process about 80% of the litter deposited in the high intertidal (Poovachiranon and Tantichodok, 1991). In field experiments, Twilley *et al.* (1997) found that mangrove crabs process the mangrove leaf litter in only one hour. Because the mangrove material is quite refractory, it may need to decompose for some time before it is useful to other invertebrates. Wafar *et al.* (1997) estimated that litter needs to decompose for about two months before it can be used in most detritivores' diets. *In situ* observations verify that mangrove leaves attract shrimp, crabs and fish (particularly juveniles), but only after four weeks of decomposition (*e.g.* Rajendran 1997; Rajendran and Kathiresan, 1999a; Fig. 6).

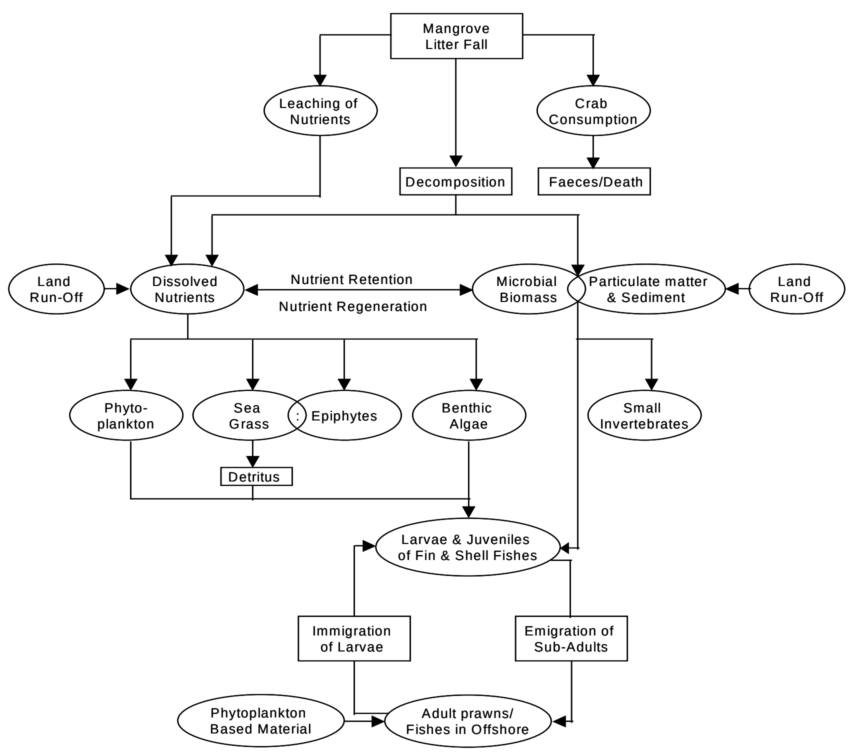

Fig. 7. A food web in a mangrove ecosystem (Kathiresan and Bingham, 2001)

Food Webs and Energy Fluxes and Interaction with Other Coastal Ecosystems

Mangals contribute to complex food webs and important energy transfers (Fig. 7). However, it is not clear how, or whether, these processes affect the larger ecosystems. While the living vegetation is a valuable food resource for insects, crustaceans and some vertebrates, most of the mangrove production is transferred to other trophic levels through litterfall and detrital pathways.

Mangrove forests produce organic carbon well in excess of the ecosystem requirements. Duarte and Cebrian (1996) estimate that the excess photosynthetic carbon approaches 40% of net primary production. While some of this organic matter simply accumulates in the sediments, large amounts could potentially be transported offshore (Alongi, 1990; Robertson *et al.,* 1991; Lee, 1995). The amount of material exported, however, depends strongly on local condition and varies enormously among mangals (Twilley *et al.,* 1992).

Materials exported from the mangroves could potentially support offshore communities (Marshall, 1994; Robertson and Alongi, 1995) but the connections between mangal and adjacent habitats are complex and dynamic, and have been difficult to demonstrate unequivocally (Alongi *et al.,* 1992; Twilley *et al.,* 1992; Hemminga *et al.,* 1995; Alongi, 1998). For instances, Jennerijahn and Ittekkot (1997) found that organic matter in continental sediments in eastern Brazil was very different from that in mangrove environments, and concluded the mangrove matter is largely retained and decomposed within the mangal itself. Studies with stable isotopes also suggest that mangroves do not make a major contribution to coastal food webs (Primavera, 1996; Loneragan *et al.,* 1997).

It appears that mangroves, in general, make only a localized contribution to the food web (Fleming *et al.,* 1990). Sediment meiofauna, for example, feed directly on mangrove detritus. The composition of the meiofaunal community changes during the process of litter decay, suggesting that the community is responding to chemical changes in the leaves (Gee and Somerfield, 1997). The meiofaunal community, though large in some habitats, may largely be a trophic dead end that contributes little to the larger food web (Schrijvers *et al.,* 1998).

The mangroves may have stronger trophic linkages with epibenthic invertebrates and fish living in the mangal and in nearby habitats (*e.g.* seagrass beds). For example, mangrove detritus contributes to the nutrition of juvenile *Penaeus merguiensis* living in tidal creeks. The juveniles feed directly on mangrove detritus, on other small detritivorous invertebrates and on benthic microalgae growing in the mangal (Newell *et al.,* 1995). Shrimp in mangrove estuaries may also feed heavily on seagrass epiphytes (Loneragan *et al.,* 1997). Invertebrates may also feed on a variety of cyanobacteria and microalgae that live on submerged portions of the mangroves and on leaf litter (*e.g.* Sheridan, 1991; Farnsworth and Ellison, 1995). Pinto and Punchihewa (1996) found that syngnathid fish (pipefish) in the Negombo Estuary of Sri Lanka fed primarily on mangrove litter. However, mangroves apparently contribute little of the carbon assimilated by other fish.

Mangrove detritus is probably more important as a substrate for microbial activity and nutrient regeneration than it is as a direct food source for detritivores. Wafar *et al*. (1997) analyzed energy and nutrient fluxes between mangroves and estuarine waters and concluded that mangroves contribute significantly to the estuarine carbon budget. However, they contribute little to nitrogen and phosphorous budgets. It is not clear whether any of these substances are exported from the mangal in sufficient quantities to make significant contributions to energy flow and the ecology of the broader ecosystems (Alongi *et al*., 1992; Alongi, 1998). Mangrove sediments efficiently uptake, retain and recycle nitrogen (Rivera – Monroy et al., 1995). Resident bacteria and benthic algae rapidly assimilate available ammonium and prevent its export (Kristensen *et al*., 1995; Middleburg *et a*l., 1996). The mangrove environment may, therefore, represent a nutrient and carbon sink rather than a source for adjacent habitats.

Mangrove ecosystems that occur towards the land prevent soil erosion and also trap soil particles. This process helps in supply of clean and nutrient-rich water for the associated ecosystems like coral reefs, seaweeds and seagrass beds. However, when the mangroves are removed, the sediment becomes loose and gets deposited on those associated ecosystems and destroys them (Fig. 8). Thus the mangroves provide protection to other marine ecosystems.

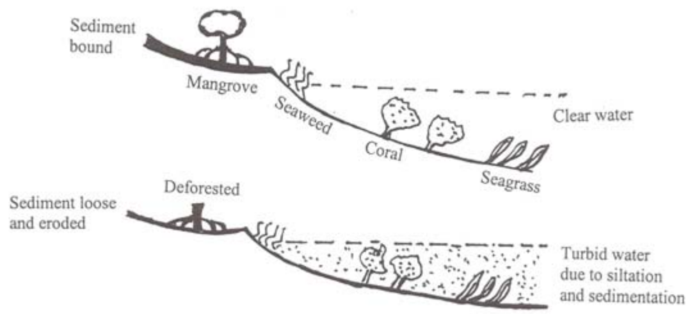

Fig. 8. Influence of mangroves and deforestation on seaweed, coral and seagrass ecosystems

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