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A review of studies on Pichavaram mangrove, southeast India

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Abstract

We studied a tropical mangrove ecosystem, situated at Pichavaram, southeast India. We found 13 species of mangrove trees, with *Avicennia marina* and *Rhizophora* species predominant, besides 73 spp. of other plants, 52 spp. of bacteria, 23 spp. of fungi, 82 spp. of phytoplankton, 22 spp. of seaweeds, 3 spp. of seagrass, 95 spp. of zooplankton, 40 spp. of meiobenthos, 52 spp. of macrobenthos, 177 spp. of fish and 200 spp. of birds. The bacteria performed activities like photosynthesis, methanogenesis, magnetic behaviour, human pathogens and production of antibiotics and enzymes (arysulphatase, L-glutaminase, chitinase, L-asparaginase, cellulase, protease, phosphatase). The microzooplankton included tintinnids, rotifers, nauplius stages of copepods and veliger larvae of molluscs, with a predominance of tintinnids. *Tintinopsis* spp. alone accounted for 90% of abundance. The macrozooplankton consisted of 95% of copepods and coelenterates. The meiofauna was rich with nematodes (50–70% of the component), followed by foramifera. The macrofauna included polychaetes, bivalves, gastropods, tanaids, isopods, amphipods, cirripedes, crabs, hermit crabs and shrimps. The mangrove harboured a large number of juvenile fishes, especially during summer and post-monsoon. The water was fertile and productive in having several fold-higher levels of nutrients, microbes, plankton and other biological resources, than the adjoining estuarine, backwater and neritic environments. The gross primary production was 8 g cm^{-3} d^{-1}; about 21% of which was contributed by phytoplankton of 5–10 μm size. Unfortunately, 90% of the mangrove cover in the study area was degraded. Possible factors that cause degradation of the ecosystem are detailed and remedial measures suggested. Techniques for regeneration of the degraded areas are proposed.

Introduction

Mangrove forests are among one of the world's most productive tropical ecosystems. They are endowed with rich and diverse living resources that provide forestry and fishery products to a large human population. They protect coastal zones from erosion, and provide food and shelter for a large number of commercially valuable fin- and shell-fishes. But mangroves are under serious threat of degradation; India has lost about 40% of its mangrove cover within this century (Krishnamurthy et al., 1987). With continuing decline of the ecosystem, it is critical to understand it better. In this regard, Pichavaram has among one of the best studied mangrove ecosystems in India. The area has already lost 75% of its green cover within this century and about 90% of the forest area is degrading (Krishnamoorthy et al., 1995). Bearing this in mind, research undertaken over three decades on various aspects of the mangrove ecosystem especially in the Centre of Advanced Study in Marine Biology of Annamalai University, is reviewed to understand its ecology and biology for a better management.

Description of the study area

The study area, Pichavaram mangrove forest (Lat. 11° 2′ N; Long. 79° 47′ E) is located between the Vellar and Coleroon estuaries (Figure 1). The forest occurs on 51 islets, ranging in size from 10 m^2 to 2 km^2, separated by intricate waterways, that connect the Vellar and Coleroon estuaries. The southern part near the Coleroon estuary is predominantly mangrove vegeta-

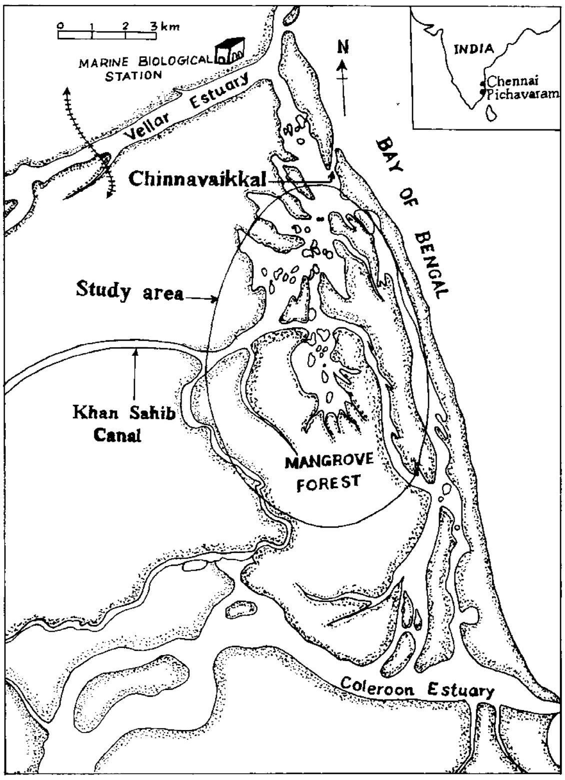

Figure 1. Study area – mangrove ecosystem lying at Pichavaram between Vellar and Coleroon estuaries along southeast coast of India.

tion, while the northern part near the Vellar estuary is dominated by mud-flats. The Vellar estuary opens into the Bay of Bengal at Parangipettai and links with the Coleroon River, which is a distributary to the River Cauvery. The Pichavaram mangrove is influenced by mixing of three types of waters: 1. neritic water from the adjacent Bay of Bengal through a mouth called 'Chinnavaikkal', 2. brackish water from the Vellar and Coleroon estuaries and, 3. fresh water from an irrigation channel ('Khan Sahib canal'), as well from the main channel of the Coleroon river (Figure 1). The mangrove covers an area of about 1100 ha, of which 50% is covered by forest, 40% by water-ways and the remaining filled by sand-flats and mud-flats (Krishnamurthy & Prince Jayaseelan, 1983). The year for convenience is arranged into four seasons: 1. post-monsoon: January–March; 2. summer: April–June; 3. pre-monsoon: July–September; and, 4. monsoon (north-east monsoon): October–December. The tides are semi-diurnal and vary in amplitude from about 15 to 100 cm in different regions during different seasons, reaching a maximum during monsoon and post-monsoon and a minimum during summer (Muniyandi, 1986). The rise and fall of the tidal waters is through a direct connection with the sea at the Chinnavaikkal mouth and also through the two adjacent estuaries. The depth of the water-ways ranges from about 0.3 to 3 m (Muniyandi, 1986).

Environmental characteristics

Solar and UV-B radiations

Radiation in the study area is high as compared to many other mangroves (Moorthy, 1995), especially during summer, it is low during monsoon. It ranges from 3.81 to 7.83 J cm^{-2} min^{-1}, with an average of 5.80 J cm^{-2} min^{-1}. Similarly, solar UV-B is high during summer (0.319 W m^{-2}, in April) and low during monsoon (0.223 W m^{-2}, in December), with an average of 0.286 W m^{-2}. Both solar and UV-B radiations are at peak in summer (April) (Moorthy & Kathiresan, 1997a).

Temperature

The atmospheric temperature varies from 28 °C (December) to 34 °C (May), the water temperature from 26 °C (December) to 30 °C (May) and sediment temperature from 25 °C (December) to 31 °C (May). Sediment temperature also varies with zone, and is higher in the upper inter-tidal (31 °C) than in the lower inter-tidal zone (28 °C) (Kathiresan et al., 1996a; Rajendran, 1997).

Rainfall

There are wide fluctuations in total rainfall and in number of rainy days between years. Annual rainfall was 1463.9 ± 329.9 mm during 1990–1998, and the number of rainy days was 53 ± 8.7. About 75–90% of total rainfall is recorded during north-east monsoon (October–December) accompanied by frequent depressions in the Bay of Bengal, while low rainfall is registered during south-west monsoon (April–June) (Kathiresan et al., 1996a).

Salinity

The salinity is maximum during summer and minimum in monsoon months. It ranges from 10 (December) to 34 g l^{-1} (April) in water and from 11.2 (November) to 31.5 g kg^{-1} (May) in sediments

(Kathiresan et al., 1996a). The ultimate source of salinity in the mangrove habitat is the neritic water, ingression of which is higher during summer than during monsoon. During monsoon, flood water dominates limiting the influence of seawater. The high temperature of summer increases evaporation, resulting in high salinity. Based on salinity data for 20 years (1971–1990), using time-series analysis, it has been predicted that salinity will increase by 5% in the year 2020 (Devi Sivasankari, 1995). This higher salinity may reduce availability of nutrients (Kathiresan et al., 1996a).

Nutrients in water

Nitrate varies from 18 to 46 μg l^{-1}, silicate from 12.3 to 112 μg l^{-1}, total phosphorus from 0.83 to 3.10 μg l^{-1} and inorganic phosphate from 0.8 to 4.78 μg l^{-1} (Perumal, 1989). Dissolved organic carbon in surface water ranges from 1.90 to 4.65 mg l^{-1}, dissolved organic nitrogen from 9.65 to 39.25 μg l^{-1} and dissolved organic phosphorus from 0.85 to 2.55 μg l^{-1}. Wind plays a role in enhancing the amount of organic matter by releasing it from sediment into the overlying water (Balasubramanian & Venugopalan, 1984). Wind velocity becomes greater (about 13 km h^{-1}) during late April–June (Krishnamurthy et al., 1995b).

Nutrients in sediments

The soil is generally clayey, rich in nitrogen, phosphorus, calcium, magnesium and in production of H_2S in the swampy fringes. The per cent of clay is more in the *Avicennia* zone, but decreases towards the back mangroves and *Rhizophora* zones. Fine sand increases towards the *Rhizophora* zone and back mangroves. The soil in the *Rhizophora* zone is higher in total nitrogen than the other two zones. Total nitrogen ranges from 2.33 (April) to 3.4 g m^{-2} (January) (Kathiresan et al., 1996a). The level is high during late-monsoon, due to freshwater, bringing abundant N_2-rich terrigenous deposits which settle on the mangrove soil. Nitrogen is higher in lower inter-tidal (3.68 g m^{-2}) than that in upper inter-tidal zone (2.4 g m^{-2}) (Kathiresan et al., 1996a). Devendran et al. (1974), Lakshmanaperumalsamy et al. (1975) , Ravikumar (1995) and Palaniselvam (1998) report bacterial fixation of nitrogen.

The fluctuations in concentration of total phosphorus between *Rhizophora* and *Avicennia* zones are much lower. But the back mangroves have a strikingly lower concentration of total phosphorus (Muniyandi, 1986). Total sediment phosphorus ranges from 0.42 (May) to 1.52 g m^{-2} (December). Its content is also higher in the lower inter-tidal (0.84 g m^{-2}) than in the upper inter-tidal zone (0.65 g m^{-2}) (Kathiresan et al., 1996a). The changes in the levels of phosphorus in sediment could be linked with the influx of phosphorus from upstream regions and with regeneration into the overlying water column under suitable conditions. Walsh (1967) reported that mud releases phosphates and nitrates during freshwater condition and absorbs them from overlying water when the water becomes saline again. Venkateswaran (1981) reported that the population of phosphatase producing bacteria was higher in mangroves than in backwaters, estuaries and marine biotopes. He also reported more phosphatase activity in clayey sediments irrespective of other environment factors.

Total sediment potassium ranges from 8.76 (August) to 28.97 g m^{-2} (January) and potassium is also higher in the lower inter-tidal (2.15 g m^{-2}) than in the upper inter-tidal zone (1.12 g m^{-2}) (Kathiresan et al., 1996a). The level of potassium is influenced by heavy rainfall resulting in the peak values during late-monsoon. Total organic carbon in sediments ranges from 0.36 to 1.95 mgC g^{-1} (Perumal, 1989).

Trace elements

Iron is the dominant trace element both in water and sediments. Dissolved iron concentration in water ranges from 69.97 to 1072 μg l^{-1} and particulate iron varies between 789.46 and 5420.4 μg l^{-1}. Sediment iron concentration ranges from 6890.24 to 26 039.93 μg g^{-1}. This high level may be due to mining at the source of the River Vellar (Subramanian et al., 1981). Total dissolved iron and manganese show a significant positive relation with salinity. The relation between salinity and dissolved copper and zinc is negative. A similar trend in accumulation of trace elements occurs in the oyster *Crassostrea madrasensis*, but not in the polychaetes of the area (Subramanian, loc. cit.).

Salinity controls the uptake and accumulation of elements in leaves of *Avicennia marina* and *Rhizophora mucronata*. The former accumulates more than the latter (Subramanian, loc. cit.). An opposite trend is seen in sediments, which show high levels of Fe, Mn, Zn and Cu near *Rhizophora apiculata* and *Bruguiera cylindrica* than near *Avicennia officinalis* and *Aegiceras corniculatum* (Glory Dally, 1984). This can be attributed to the fact that the former two species are capable of excluding salts and metals during absorption, whereas the latter two absorb them. In general, mangrove plants have extremely low trace metal concentration, as compared to the sediments, which are a large reservoir of trace elements. Changes in concentration of elements are controlled by shifting in and out of the sediments rather than by accumulation and excretion by plankton (Subramanian, loc. cit.). Some chelating agents like humic substances form complexes with heavy metals, thereby reducing bioavailability of metals to plants and preventing toxicity. The concentrations of particulate humic acids (18.08 mg l^{-1}) and dissolved humic acids (7.95 mg l^{-1}) are relatively higher in the mangrove habitat than in other coastal environments (Perumal, 1985).

Pesticides

The mangrove habitat is not polluted with agricultural pesticides. Persistent organochlorine residues such as, $\sum$ HCH (sum of α β γ δ isomers) and $\sum$DDT (sum of p, p′DDE, p, p′DDD and o, p′DDT) in the study area are very low (Ramesh et al., 1990, 1991). The maximum level of $\sum$HCH is 0.6 μg l^{-1} in mangrove water against 3.9 μg l^{-1} in the nearby Vellar estuary during wet season. The maximum is 0.017 μg g^{-1} in mangrove sediment during wet season. DDT values are much lower than the $\sum$HCH, ranging from 0.0003 to 0.002 μg l^{-1}. The o, p′-DDT is abundant (40%) in mangrove sediments during the wet season, as compared to dry season (20%). The p, p′DDD is a dominant metabolite (50%) in the mangrove sediments during dry season (Ramesh, loc. cit.).

Fertility of mangrove waters

In the study area, as importance of mangroves in enriching the coastal sea has been established. The turbidity and seston content of mangrove water are, respectively, 55 and 20 times more than those of the nearby sea (Krishnamurthy & Prince Jayaseelan, 1984). The silicate concentration is about 10 times higher in mangrove water (105 μg l^{-1}) than in sea water (11 μg l^{-1}). The concentration of nitrate, inorganic phosphate, and dissolved organic carbon of mangrove water are four, 20 and two times, respectively, those of sea water (Krishnamurthy & Prince Jayaseelan, loc. cit.). The nutrient-rich mangrove water, when mixed with comparatively nutrient-poor coastal waters by tidal ebb and flow, cause an increase of fertility and productivity of the coastal waters of Bay of Bengal (Krishnamurthy et al., 1987). It is estimated that the study area of mangroves exports 10% (261 t C yr^{-1}) and 60% (1566 t C yr^{-1}) of total organic matter to the neighbouring estuaries and sea. Only 30% (783 t C yr^{-1}) are retained and used within the mangrove (Subramanian et al., 1984).

Floral studies

Algae and seagrass species

A total of 22 species of seaweeds has been recorded in the mangrove, of which 11 species belong to green, two species to brown and the remaining nine species belong to red algae (Kannan & Thangaradjou, 1998). Twenty species of blue-green algae have been recorded (Krishnamurthy et al., 1995a).

Only three seagrasses are found, of which two species (*Halophila ovalis* (R.Br.) Hook; *H. beccarii* Asch.) belong to the Hydrocharitaceae and the remaining (*Halodule pinifolia* (Miki) Hartog) to the Potamagetonaceae (Kannan & Thangaradjou, 1998).

Mangrove species

Floristic composition, zonation and pollen spectra have been studied by Venkatesan (1966), Caratini et al. (1973), Blasco (1975), Blasco et al. (1975), Krishnamurthy et al. (1981) and Muniyandi (1986). Kathiresan & Ramanathan (1997) reported 13 species of true mangrove species, beside 73 spp. of other vegetation, which include 24 tree, 21 shrub, 28 herb, seven climber, three parasite and three creeper species. By degree of abundance, *Avicennia marina* is the most common species, followed by *Rhizophora apiculata, R. mucronata, Bruguiera cylindrica, Excoecaria agallocha, Ceriops decandra, A. officinalis, Aegiceras corniculatum, Rhizophora annamalayana, Acanthus ilicifolius* and *Lumnitzera racemosa*. *Xylocarpus granatum* and *Sonneratia apetala* are rare. *Kandelia candel* is extinct in the study area (Muniyandi, 1986). A species new to science, *Rhizophora annamalayana*, has been described, but is a hybrid between *R. apiculata* and *R. mucronata* (Kathiresan, 1995a). Previously it was identified as *R. lamarckii* (Muniyandi & Natarajan, 1985). Recently, intraspecific genetic variability in *Acanthus ilicifolius* was assessed by DNA-based molecular markers (random amplified polymorphic DNAs and restricted fragment length polymorphisms). *Acanthus ilicifolius* was found to have 48 genotypes with eight distinct populations, but there was no difference in chromosome number (2 n=48) at either intra- or inter-population levels (Lakshmi et al., 1997). A greater degree of polymorphism has been detected in *Excoecaria agallocha* than in *Acanthus ilicifolius* and *Avicennia marina*. In *E. agallocha*, genetic polymorphism is species-specific and independent of morphological and sexual differences (Parani et al., 1997).

Leaf and flower phenology

Leaf formation peaks in pre-monsoon and monsoon, coinciding with heavy rainfall, while leaf shedding peaks during post-monsoon. The average life time of a leaf of *Rhizophora* and *Avicennia* is around 13.5 months (Muniyandi, 1986). Flowering is at peak in summer (*Bruguiera cylindrica, Ceriops decandra*), pre-monsoon (*Avicennia* spp. and *Rhizophora* spp.) or in monsoon and post-monsoon (*Lumnitzera racemosa* and *Aegiceras corniculatum*) (Elangovan, 1993). The development time of a flower from visible bud primordium is 22 months for *Rhizophora apiculata* and 7 months for *Avicennia marina*. The viviparous propagule takes 8 months to grow to full length after fertilization in *R. apiculata* and 16 months in *R. mucronata*. In general, fruiting and dispersal take place in the rainy season (Muniyandi, 1986).

Litter production, decomposition and nutrient enrichment

Annual litter production by *Rhizophora mucronata, R. apiculata* and *Avicennia marina* is 1456 , 1361 and 624 g m^{-2}, respectively (Muniyandi, 1986). Variations in the amount of litter fall between years, are noticeable, depending on weather and rainfall. Leaves are the major component of litter, with up to 63.2% in *R. mucronata* and 86.7% in *A. marina* (Muniyandi, loc. cit.). In the surrounding water, the decomposition of *A. marina* leaf litter is quick compared to that of *Rhizophora* species. On the soil, *R. mucronata* leaf litter decomposes at a faster rate than that of *R. apiculata* and *A. marina* (Muniyandi, loc. cit.). During decomposition, nutrients are released into the water and it is calculated that *R. apiculata* contributes annually 0.047 t of nitrogen, 0.0071 t of phosphorus and 0.019 t of potassium to per ha area of mangrove; *R. mucronata* contributes 0.022 t of N_2, 0.0054 t of P and 0.01 t of K; *A. marina* contributes 0.003 t of N_2 , 0.0054 t of P and 0.20 t of K (Muniyandi, loc. cit.).

The role of bacteria and fungi in decomposition of mangrove litter has been extensively studied (Rajendran, 1997). The fungi are the primary invaders, showing a peak population in the early period of decomposition. Fungi like *Aspergilli* are capable of producing tannase to degrade tannins and hence are capable of colonizing mangrove litter, rich in tannins. As these tannins are inhibitory, the bacterial populations are low in the initial period of decomposition. But the leaching of tannins from litter coincides with a rapid increase in bacterial load on mangrove leaves. Of the heterotrophic bacteria, nitrogen-fixing azotobacters significantly increase with leaf litter decomposition (Figure 2). One of the significant nutrient changes associated with leaf decomposition is an increase in total nitrogen, which is about three-times higher in decomposed than in undecomposed leaves (Figure 2; Rajendran, 1997). This high counts of N_2-fixing azotobacters and high levels of total N_2 in decomposing leaf litter attract animal resources (Figure 2) such as

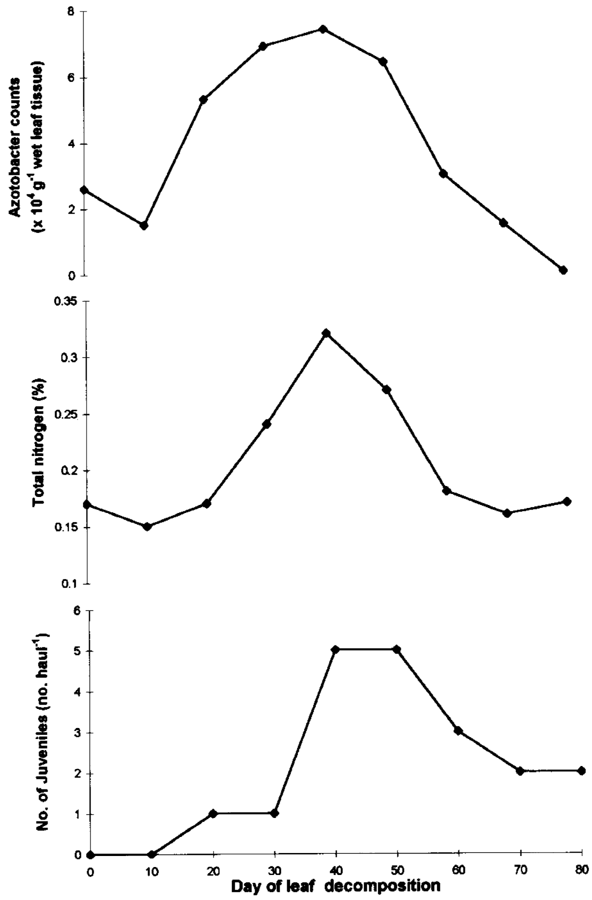

Figure 2. Changes in the nitrogen-fixing azotobacter counts ($\times$ 10^4 g^{-1} leaf tissue), the total nitrogen content (% of leaf tissue) and the juvenile prawns (no. $haul^{-1}$) associated with decomposing senescent leaves of *Avicennia marina*, kept in nylon bags (35 cm $\times$ 35 cm, 2 mm mesh size) and submerged in mangrove waters at Pichavaram, during July–September, 1996. (Source: Rajendran, 1997).

isopods, amphipods, young oysters, prawns, crabs and fishes (Subramanian et al., 1984). Based on this observation, a 'mangrove vegetation trap' technique has been proposed to increase fish catch, by aggregating thickets of mangrove twigs in the estuarine waters and allowing them to decompose; netting around these thickets yields about three-fold higher fish and prawn catches (Rajendran, 1997; Rajendran & Kathiresan, 1998).

Microbiological aspects

The fertility of mangrove water results from the decomposition of organic matter and recycling of nutrients by micro-organisms. Microbial counts are high during monsoon months (Kathiresan et al., 1998), when nutrients are brought in by freshwater ingression (Kathiresan et al., 1996a). In general, the microbial population is about seven-fold greater in mangrove water than in adjoining Bay of Bengal. Among micro-organisms, the ratio between fungal and bacterial populations is about 1:7000 (Krishnamurthy et al., 1987). In all, 52 species of bacteria and 23 of fungi have been recorded.

Bacterial flora

Photosynthetic bacteria of the mangrove sediments include two major groups viz., purple sulphur bacteria (family Chromatiaceae, strains belonging to *Chromatium* sp.) and purple non-sulphur bacteria (family Rhodospirillaceae, strains belonging to *Rhodopseudomonas* sp.). The growth of *Rhodopseudomonas* is maximum at 30 g l^{-1} salinity and 6–8 pH; bacterial chlorophyll accumulates (4.1 μg l^{-1}) at 20 g l^{-1}; and ammonia is the best inorganic source for growth of the phototrophic bacteria, under laboratory conditions (Vethanayagam, 1991). The mangrove biotope has higher values of bacterial chlorophyll- *a,c,d* than neritic and estuarine biotopes (Paneerselvam et al., 1979).

The mangrove sediment harbours larger bacterial population than the water column (Ravikumar, 1995). This is attributed to nutrient accumulation, precipitation of inorganic compounds and settlement of dead organic matter in the sediments. Common genera are *Vibrio, Bacillus, Micrococcus, Pseudomonas, Aeromonas, Flavobacterium* etc. (Sathiyamurthy et al., 1990). Certain rare forms of bacteria are present in the mangrove environment. A methanogenic bacterium, *Methanococcoides methyluteus*, has been isolated and characterised from the sediment (Mohanraju et al., 1997). Methanogenic bacteria are high during summer and pre-monsoon and low during monsoon and post-monsoon (Ramamurthy et al., 1990). Certain bacterial strains, isolated from mangrove sediments, exhibit magnetic behaviour. These magnetobacteria include *Pseudomonas mesophilica, P. caryophylls* and *Bacillus cereus* (Saravanan, 1995).

Nitrogen-fixing *Azotobacter* species are more common in mangrove sediments than in marine, backwater and estuarine systems (Lakshmanaperumalsamy, 1987). Three species of azotobacter viz., *A. vinelandi, A. beijerinckii* and *A chroococcum* have been identified. These species are promising for their utility as biofertilizer in prawn ponds and for mangrove nurseries. Growth of the bacteria increases with level of NaCl up to 30 g l^{-1}, but tannins reduce their growth and nitrogen fixing activity (Ravikumar, 1995). Nitrogen-fixing cyanobacteria extracted from the study area, comprise 15% of total phytoplankton and exhibit a peak in cell counts during summer (Ramachandran & Venugopalan, 1987). The aerial roots of mangroves are rich in epiphytic cyanobacterial populations, especially in the lower and middle portions, during summer and post-monsoon (Palaniselvam, 1998). Cyanobacterial species, especially of *Phormidium*, are well-adapted to saline stress (up to 250 g l^{-1}). The species of *Phormidium* are promising for biofertilizer applications and in shrimp feed formulations (Palaniselvam & Kathiresan, 1998a, b; Palaniselvam et al., 1998). Culture techniques for growing the cyanobacterial species have been perfected (Palaniselvam & Kathiresan, 1996).

Vibrio parahaemolyticus, a pathogenic bacterium involved in food-borne gastro-enteritis, associated primarily with human consumption of contaminated seafood, does occur in the mangrove habitat (Martin et al., 1979). The bacterial counts are high at low salinities and less at salinities >28 g l^{-1}. The numerical fluxes of *V. parahaemolyticus* and other vibrios closely follow the quantitative abundance of zooplankton (Martin, loc. cit.). *Vibrio parahaemolyticus* is absent in plankton harvested during summer months. In contrast, phytoplankton blooms do not exert significant influence on the counts of *V. parahaemolyticus* and other vibrios associated with plankton. A quantitative survey of the incidence of *V. parahaemolyticus* in freshly caught fin- and shell-fishes revealed that about 50% of animals harbour the pathogen during monsoon (Martin, loc. cit.). Another human pathogen, *E. coli*, has also been studied in the mangrove habitat. In general, 20% of fin-fish are positive for it. The bacterial species peaks in monsoon and is low during summer and late post-monsoon (Ramesh, 1988).

The mud crab, *Scylla serrata*, has a higher bacterial count in its gut than other crabs (*Charybdis cruciata, Podophthalmus vigil, Portunus pelagicus* and *P. sanguinolentus)*. *Scylla serrata* lives in or near the bottom of mangroves, whereas the other four crabs are mostly free-swimming. The midgut of *S. serrata* harbours most aerobic and proteolytic bacteria. Luminescent bacterial flora are predominant in the hind gut and on the cuticular membranes of all the crabs (Venkateswaran et al., 1981).

The abundance and activities of bacteria are controlled by various physical chemical factors of the mangrove ecosystem. One such variable is tannins, leached from mangrove litter (Kathiresan et al., 1998). Bacterial counts reach a peak during October, coinciding with the lowest tannin concentration. Increasing tannin concentration is associated with decreasing bacterial counts from November onwards. Thus, tannin plays a role in keeping the bacterial counts low and outbreaks of virulent pathogens down (Kathiresan et al., 1998). The counts of heterotrophic bacteria are higher on fresh leaves of mangroves than on leaf litter. The high bacterial counts also coincide with higher leakiness of amino acids and sugar, and lower leakiness of tannins from the mangrove leaves (Kathiresan & Ravikumar, 1995a).

Microbial enzymes from the mangrove environment have also been studied. About 71% of bacterial strains produce L-asparaginase. This enzyme has better anti-leukemic activity in humans than that extracted from non-mangrove sources (Selvakumar, 1981). Also, halophilic bacteria (*Halococcus*) isolated from mangrove sediments, produce L-asparaginase (Sudha, 1981). Arylsulfatase, an important enzyme that participates in the metabolism of sulphuric acid esters, is produced predominantly by *Bacillus*, followed by *Vibrio*. Enzyme activity is highest, ranging from 21.61 to 32.61 μg phenolphthalein g^{-1}, in the mangrove, followed by the backwater and estuary. Arylsulphatase exerts maximum activity during summer and premonsoon (Chandramohan et al., 1974; Devendran, 1977). Certain bacteria exhibit high phosphatase activity, capable of solubilizing phosphate (Sundararaj et al., 1974). The mangrove sediments exhibit a higher activity of L-glutaminase than sediments from other biotopes; and clayey sediments show higher enzyme activity than silty ones (Dharmaraj et al., 1977). One hundred and eight strains of bacteria show chitin - degrading activity (Babu Rajendran, 1989).

Fungal flora

Fungal studies were carried out in the 1980s. The predominant mycoflora is *Aspergillus* and *Penicillium*. Some 23 species of fungi are present, with the majority belonging to the Deuteromycetes. Salinity correlates negatively but pH and dissolved oxygen do not show any significant influence on mycoflora. Water is not as favourable as sediments. Fungal counts in rhizosphere soil are maximum in monsoon and minimum during summer (Mohamed Salique et al., 1985; Venkatesan & Natarajan, 1986).

Ten species of epiphytic fungi, isolated from mangrove leaves, show a negative correlation with leaf tannins (Sivakumar & Kathiresan, 1990). Fungal counts are higher on mangrove leaf litter than on fresh leaves. High fungal counts on leaf litter coincide with low content of tannins and sugars, high level of amino acids, low leakiness of tannins and sugars, and high leakiness of amino acids from leaf litter (Ravikumar & Kathiresan, 1993).

Actinomycetes, mostly *Streptomyces* species, have been isolated by Lakshmanaperumalsamy (1979). About 75% of strains exhibit antibiotic activity (Vanaja Kumar, 1981). An antibiotic compound-β-unsaturated γ-lactone from *Streptomyces grisebrunneus*, showing wide-range anti-microbial activity, has been isolated and identified (Balagurunathan, 1992). Besides this, the streptomycetes produce cellulase that degrades cellulolytic waste materials (Chandramohan et al., 1972). The streptomycetes isolated from the digestive tract of the marine borer *Barnea birmanica* also exhibit cellulolytic activity (Balasubramanian et al., 1979).

Plankton

Phytoplankton

Biomass and production of phytoplankton are important in regulating the diversity of organisms at higher tropic levels. The mangrove water had significantly richer nannophytoplankton than the estuary (Subramanian, 1981). The phytoplankton of 5–10 μm size contributed 33–51% of total chlorophyll-a and 20–22% of total gross production in mangrove water (Kawabata et al., 1993). The population density of the diatom species ranges between 1.6×10^3 and

7.5×10^5 and of dinoflagellates between 0 and 9.2×10^4 (Santhanam et al., 1975). There are 82 species of phytoplankton, which include 67 species of diatoms, 12 species of dinoflagellates and three species of blue-green algae. The diatoms form the bulk, with 72% of the census, followed by the dinoflagellates with 15% (Kannan & Vasantha, 1992). Natural phytoplankton communities are dominated by *Nitzschia closterium*, *Pleurosigma* species, *Thalassionema nitzschioides* and *Thalassiothrix frauenfeldii* (Mani, 1992). Thirty one species are bloom formers with a predominance of *Rhizosolenia alata f. gracillima*, attaining a maximum bloom concentration of 2881×10^7 μm^2 l^{-1} (Mani, 1994). In the mud-flat regions, more phytoplankton species, especially pennate diatoms rather than centric ones, are encountered, from 1129 to 4686 organisms g^{-1} of mud. There are 51 species belonging to 23 genera of benthic diatoms, rare during monsoon but common during summer (Jayachandaran, 1990). Unlike the estuary, the mangrove harbours many species of epiphytic diatoms attached to the submerged roots of vegetation, particularly woody species of *Rhizophora* (Krishnamurthy et al., 1987).

The primary production values in the study area are high as compared to other areas–gross production is 8 gC m^{-3} d^{-1}, while net primary production is as high as 6.3 gC m^{-3} d^{-1} (Krishnamurthy & Sundararaj, 1973). In comparison, production rates are 5 gC m^{-3} d^{-1} in Ivory coast, 2.4 gC m^{-3} d^{-1} in Mexico coast (Robertson et al., 1992) and 0.0693 gC m^{-3} d^{-1} in the Fly River delta (Papua, New Guinea) (Robertson et al., 1992). Chlorophyll-*a* shows a peak value of 30 mg m^{-3} and a negative relation with species diversity of phytoplankton. The benthic photosynthesis is higher (0.41 gC m^{-2} d^{-1}) in the interior than in the lower reaches of mangroves (0.29 gC m^{-2} d^{-1}) (Krishnamurthy et al., 1987).

The work of Krishnamurthy et al. (1974), Santhanam et al. (1975), Krishnamurthy & Santhanam (1980), Mani (1992, 1994) and Kannan & Vasantha (1992) provides information on species diversity and distribution of phytoplankton. Other studies include phytoplankton pigments (Sundararaj & Krishnamurthy, 1974; Paneerselvam et al., 1979), and the phytoplankton in relation to nutrients and environmental features (Krishnamurthy & Sundararaj, 1973; Sundararaj & Krishnamurthy, 1975).

Zooplankton

The annual mean value of zooplankton is 12×10^4 organisms m^{-3}, higher in the mangrove than in backwater and estuarine waters (Santhanam et al., 1975). These numbers are significantly higher than what is often recorded offshore (reviewed by Robertson & Blaber, 1992). Zooplanktonic larvae range from 0.11 to 0.35×10^4 organisms m^{-3} in surface waters and from 0.098 to 0.56×10^4 m^{-3} in bottom waters of mangrove channels in Coleroon estuary. Larval recruitment in Coleroon estuary occurs due to the influx of Pichavaram mangrove waters during low tide and the influx of coastal waters at high tide (Ayyakkannu, 1989).

The microzooplankton includes tintinnids, rotifers, nauplius stages of copepods and veligers of bivalves and gastropods. Among microzooplankton, the ciliates (tintinnids) are dominant. Of tintinnids, *Tintinnopsis* spp. alone accounts for 90% by census, followed by *Favella*. Higher numbers of tintinnids are observed during summer and lower numbers during monsoon (Godhandaraman, 1994; Krishnamurthy et al., 1995a). There are 40 species of rotifers belonging to 17 genera, with a predominance of *Brachionus* spp. especially during postmonsoon and monsoon (Govindasamy & Kannan, 1991; Krishnamurthy et al., 1995a).

The macrozooplankton consists copepods and coelenterates (95%), macro-metazoans constitute the remaining 5%. Of 39 species of copepods recorded, 25 are Calanoids, 7 spp. Cyclopoids and 7 spp. Harpacticoids. Low number of copepods are recorded in monsoon (Kaliyaperumal, 1992).

Meiobenthos

Free-living nematodes from Indian mangroves have only been studied in the present study area (Sultan Ali et al., 1983). They represent about 50–70% of total meiobenthic animals. The foraminifera stands second to nematodes. However, during monsoon, the populations of foraminifera increase while the nematodes decrease. A high density of nematodes (3.8×10^4 m^{-2}) was observed during summer and a low density ($1.96 \times 10^4 m^{-2}$) during winter (Sultan Ali, loc. cit.). About 40 species were recorded, among which *Teschellingis longicaudata*, *Paracomesoma longispiculum* and *Pasmodora luticola* were dominant. The lower reaches of mangroves, influenced by freshwater inflow, supported most species of nematodes; the interior mangrove had only a single species (*T. lon-*

Table 1. Macro-invertebrate benthic fauna recorded form Pichavaram mangroves along southeast coast of India. Their dominant microhabitats are given in the brackets(Source: Balasubrahmanyan, 1994; Rajendran, 1997)

Polychaeta
Heteromastus similis (subtidal)
Euclymene annandale (subtidal)
Perinereis sp. (oysters)
Mercierella enigmatica (stilt and breathing roots)
Bivalvia
Crassostrea madrasensis (stilt roots)
Gastropods
Dostia (Neritina) *crepidularia* (stilt and breathing roots)
Telescopium telescopium (intertidal)
Cerithidea fluviatilis (intertidal)
Cerithidea obtusa (intertidal)
Littorina scabra (terrestrial, on plant surface)
Assiminea nitida (stilt and breathing roots)
Pythia plicata (terrestrial)
Melampus ceylonicus (terrestiral)
Cassidula nucleus (terrestrial)
Cirripedia
Balanus amphitrite (stilt and breathing roots)
Tanaidacea
Tanais sp. (on oyster)
Apseudes gymnophobia (subtidal)
Halmyrapseudes killaiyensis (subtidal)
Isopods
Ligia exotica (terrestrial)
Cirolana fluviatilis (on oyster)
Sphaeroma terebrans (wood borers in aerial roots)
Sphaeroma annandalei (wood borers in aerial roots)
Amphipoda
Paracalliope sp. (subtidal)
Grandidierella sp. (on oyster)
Corophium triaenonyx (on oysters)
Talorchestia sp. (stranded algae)
Decapoda - Anomura
Scylla serrata (subtidal)
Scylla tranquebarica (subtidal)
Thalamita crenata (subtidal)
Heteropanope indica (on oyster)
Ptychognathus altimanus (intertidal burrows)
Sesarma pictum (intertidal burrows)
Sesarma edwardsi (intertidal burrows)
Sesarma bidens (intertidal burrows)
Sesarma plicatum (intertidal burrows)

Table 1. Continued

Sesarma andersoni (subtidal)
Sesarma brockii (intertidal burrows)
Neoepisesarma mederi (intertidal burrows)
Neoepisesarma tetragonum (intertidal burrows)
Nanosesarma batavicum (on oyster)
Uca (Celuca) *lactea annulipes* (intertidal)
Macrophthalmus depressus (intertidal)
Macropthalmus erato (intertidal)
Metapograpsus maculatus (intertidal)
Metapograpsus messor (subtidal)
Metaplax elegans (subtidal)
Metaplax distincta (subtidal)
Decapoda-Caridea
Penaeus indicus (subtidal)
P. monodon (subtidal)
P. semisulcatus (algal & seagrass beds, subtidal)
P. merguiensis (subtidal)
Metapenaeus monoceros (subtidal)
M. affinis (subtidal)
M. dobsoni (subtidal)
M. brevicornis (subtidal)
M. lysianassa (subtidal)
Alpheus malabaricus (intertidal)

gicaudata), dominant over all others (Sultan Ali, loc. cit.).

Macrobenthos

The macro-invertebrate benthic fauna of the mangrove consists mostly of the estuarine fauna of the Vellar and Coleroon estuaries, which includes polychaetes, bivalves, gastropods, tanaids, isopods, amphipods, cirripedes, crabs, shrimps and hermit crabs (Table 1; Maruthamuthu et al., 1985; Kasinathan & Shanmugam, 1986; Maruthamuthu & Kasinathan, 1986; Shanmugam & Kasinathan, 1987; Shanmugam 1991a,b, 1994, 1995a,b,c, 1996; Sethuramalingam & Ajmal Khan, 1991; Balasubrahmanyan, 1994; Dious & Kasinathan, 1994; Rajendran, 1997). Most are detritus feeders. Terrestrial gastropods such as *Cerithidea obtusa, Littorina scabra, Pythia plicata, Melampus ceylonicus, Cassidula nucleus,* and the isopod *Ligia exotica,* are declining (Balasubrahmanyan, 1994).

The population of juvenile mud crab, *Scylla serrata* is highest in the seagrass and algal bed areas. Crabs of 20–30 mm carapace width domin-

Table 2. Larval development of crabs collected from Pichavaram mangrove forests, reared under laboratory conditions

Name of crab species	Total no. of days to reach first crab stage		No. of zoeal stages	Reference
Metapograpsus maculatus	-	(38)	5	Pasupathi & Kannupandi (1986)
Sesarma brockii	11[a]	(8)	4	Vijayakumar & Kannupandi (1987)
Sesarma bidens	36	(7)	4	Krishnan & Kannupandi (1987)
Sesarma pictum	16	(7)	4	Pasupathi & Kannupandi (1987)
Metaplax elegans	17	(9)	5	Pasupathi & Kannupandi (1988a)
Macrophthalmus depressus	23	(11)	5	Pasupathi & Kannupandi (1988b)
Metaplax distincta	19	(9)	5	Krishnan & Kannupandi (1989)
Sesarma edwardsi	16	(9)	4	Kannupandi & Pasupathi (1994)

[a] Days to reach megalopa; values in brackets are the days of zoeal development; – first crab not obtained.

ate the population in the shallow intertidal zones (Chandrasekaran & Natarajan, 1994). Several crab species, collected from the study area, have been successfully reared from hatching to first crab in the laboratory (Table 2).

Prawns and finfish

Mangrove water serves as nursery ground to juvenile fishes (Table 3) e.g. mullet (*Mugil cephalus* and *Liza* sp.) (Chandrasekaran & Natarajan, 1993) and flatfishes (*Pseudorhombus arsius, P. elevatus, Brachirus orientalis* and *Cynoglossus puncticeps*) (Rajaguru et al., 1988). About 10 groups of fish eggs, 53 groups of early developmental stages and 177 species of juveniles have been recorded in the study area (Prince Jeyaseelan, 1983). The neritic waters have the greatest influence on the fishery resources: 99 species of fishes are found here (salinity 30–35 g l^{-1}) against only 25 species, when fresh water inundates the mangrove (salinity < 0.5 g l^{-1}) (Prince Jeyaseelan, 1983). There are eight penaeid species, with a predominance of *Metapenaeus monoceras* and *Penaeus indicus;* they yield a greater catch in the core mangrove areas than in open water (Rajendran, 1997). Summer and post-monsoon are the periods of seed abundance for prawn and finfish, whereas population density is low during early monsoon. Relatively more prawn seed can be collected during low tide than during high tide and more during the night than in day time (Rajendran, 1997).

In general, prawns lack sterol synthesizing ability and require a dietary source of cholesterol as essential nutrient for normal development and growth especially at juvenile stages. Juvenile prawns are abundant in mangroves which are rich in cholesterol. It has been shown experimentally that the cholesterol, extracted from *Rhizophora* leaves promotes growth, conversion efficiency and improves biochemical constituents of juvenile *Penaeus indicus* (Ramesh & Kathiresan, 1992).

Insects and avifauna

Many insects, especially mosquitoes (*Aedes reginae*, *Ae. albopictus*, *Ae. wardi*, *Anopheles subpictus* and *Culex brevipalpis*) are abundant during monsoon in the study area (Thangam, 1990; Thangam & Kathiresan, 1993a).

The avifauna is the top of the mangrove food chain. About 200 species, among which 36 shore birds occur. The common birds includes herons, storks, sea eagles, egrets, kingfishers, sand-pipers and whistlers. Their migratory season starts from October and lasts till March (Sampath & Krishnamurthy, 1990).

Responses of mangrove flora and fauna to environmental stresses

Solar radiation and UV-radiation

In the field, most *Rhizophora* seedlings successfully sprout under the shady canopy (Kathiresan & Ramesh, 1991). *Rhizophora* seedlings, when grown in the shade, showed optimal growth, highly efficient NO_3 use and efficient photosynthesis (Kathiresan & Moorthy, 1993).

Species of Rhizophoraceae exhibit higher UV-B tolerance than *Avicennia* or other succulent plants (Moorthy & Kathiresan, 1997a). There are many

Table 3. Size range of fin- and shell-fishes abundantly present in the Pichavaram mangrove waters, along southeast coast of India (Source: Kathiresan, 1999)

Name of species	Size range recorded in mangroves (mm)	Maximum size recorded in off-shore (mm)
Shell-fish		
Penaeus indicus	22–62	230
P. monodon	17–112	320
P. semisulcatus	20–50	250
P. merguiensis	19–94	240
Metapenaeus monoceros	14–68	180
M. affinis	18–48	180
M. dobsoni	18–55	130
M. brevicornis	16–39	140
M. lysianassa	11–44	90
Scylla serrara	29–140	211[a]
S. tranquebarica	90–175	220[a]
Fin-fish		
Ambassys gymnocephalus	19–45	60
A. commersoni	28–68	80
Arius subrostratus	70–230	320
Chanos chanos	89–174	1800
Etroplus suratensis	48–118	400
Gerres filamentosus	48–82	250
G. abbreviatus	38–68	250
Liza parsia	68–158	160
L. macrolepis	88–128	600
L. subviridis	33–68	300
Lates calcarifer	122–380	2000
Lutjanus argentimaculatus	83–146	1200
Mugil cephalus	108–248	900
Osteomugil cunnesius	64–184	410
Pomadasys kaakan	30–83	800
Plotosus canius	31–175	1500
Scatophagus argus	68–108	300
Siganus javus	48–93	450
S. canaliculatus	35–72	300
Terapon jarbua	39–60	300

[a]Carapace width.

changes in photosynthesis and biochemical constituents in *Rhizophora apiculata* seedlings grown experimentally under UV-B regimes predicted for 10, 20, 30 and 40% stratospheric ozone depletions (Moorthy & Kathiresan, 1997b). Seedlings exposed to low UV-B radiation (10%) show an increase of 45% in net photosynthetic rate (pN). Under high UV-B (40%), a 59% drop in pN occurs (Moorthy, 1995). Anthocyanin concentrations drop with increasing UV-B doses, but phenols and flavonoids increase (Moorthy & Kathiresan, 1997b). Small UV-B doses enhance levels of amino acids – aspartate, glutamine, asparagine, serine, glutamine, threonine and histidine; this effect is reversed at higher doses; irrespective of the doses, the activity of nitrate reductase is inhibited while simultaneously enhancing total tissue nitrate (Moorthy & Kathiresan, 1998). Seedlings irradiated with higher doses of UV-B show a characteristic decline of specific proteins with molecular weights of 17, 23 and 33 KDa. In contrast, low UV-B irradiation results in an increase in proteins of 17, 23, 25, 33 and 55 KDa. UV-B, in general, enhances saturated fatty acids and reduces unsaturated fatty acids (Moorthy & Kathiresan, 1998).

Growth and biochemical responses of the green tiger prawn (*Penaeus semisulcatus*) reveal that the head region, specifically the eye-stalk, absorbs the UV-B radiation (Kathiresan & Moorthy, 1996).

Salinity, soil conditions and tidal gradients

Mangrove seedlings require low salinity; their salt requirements increase with growth. In general, mangrove vegetation tends to be more luxuriant at lower salinities (Kathiresan et al., 1996b). Hydroponically grown *Rhizophora* seedlings perform better in 30 g l^{-1} for *R. mucronata* and in 15 g l^{-1} for *R. apiculata* (Kathiresan & Thangam, 1990a; Kathiresan et al., 1996b).

Rhizophora apiculata seedlings do better in plantation sites with high potassium levels (Kathiresan et al., 1994b). After monsoon, low salinity and high nutrient concentrations produce rapid growth; the seedlings grow 5× as much and produce 4× as many leaves as in the dry season (Kathiresan et al., 1996a). High salinity stunts tree growth in *A. marina* stands (Selvam et al., 1991). The seedlings in the lowest intertidal zone grow 2.5 times faster and sprout 4 times as many leaves as seedlings in the highest zone (Kathiresan et al., 1996a). Ellison & Farnsworth (1993) made similar observations in *Rhizophora mangle* of Caribbean.

Other stresses

There may be allelopathic interactions among mangrove species, implying interspecific competition. Leachates from leaf litter of some mangrove and salt marsh species (e.g. *Suaeda monoica, Lumnitzera racemosa, Ceriops decandra* and *R. apiculata)* inhibit the growth of roots and shoots of *Rhizophora apiculata* and of *R. mucronata* seedlings. The effect has been attributed to toxic compounds present in the leaf leachings (Kathiresan & Thangam, 1989; Kathiresan et al., 1993).

Novel activities of mangroves

Mangroves are biochemically unique. For example, *Excoecaria agallocha* exudes an acrid latex that is injurious to the human eyes. Also the latex has a 'knock-down' effect on a variety of marine organisms (Kathiresan & Thangam, 1987; Kathiresan et al., 1987; Kathiresan et al., 1990). Mangrove extracts kill larvae of mosquitoes (Table 4) – *Anopheles stephensi* (Thangam & Kathiresan, 1988), *Culex tritaeniorhynchus* (Thangam & Kathiresan, 1989), *Aedes aegypti* (Thangam & Kathiresan, 1991, 1993a, 1994) and *Culex quinquefasciatus* (Thangam & Kathiresan, 1997). Extract applied directly to human skin repel adult *Aedes aegypti* (Thangam & Kathiresan, 1993b). Smoke from burned extracts both repel and kill *Aedes aegypti* (Thangam et al., 1992) and *Culex quinquefasciatus* (Thangam & Kathiresan, 1992b). Of the mangrove substances tested to date, *Rhizophora* spp. show the strongest mosquito larvicidal activity (Table 4); a pyrethrin-like compound has been isolated and identified (Thangam, 1990).

Mangroves have long been used in folk medicine to treat diseases. The extracts have proven activity against human, animal and plant pathogenic viruses including, Human immuno-deficiency virus (Premanathan et al., 1996), Semliki forest virus (Premanathan et al., 1995), Tobacco Mosaic Virus (Padmakumar & Ayyakkannu, 1997), Vaccinia virus (Premanathan et al., 1994a), Encephalomyocarditis virus (Premanathan et al., 1994b), New castle disease virus (Premanathan et al., 1993), and Hepatitis B viruses (Premanathan et al., 1992; Table 4). A few mangrove species, particularly the Rhizophoraceae, have high antiviral activity (Table 4; Premanathan et al., 1992: Kathiresan et al., 1995a). Purified fractions of polysaccharides (galactose, galactosamine, glucose and arabinose) exhibit potent anti-HIV activity (Premanathan et al., 1999). Radical modulation activity of lignins from the leaf of *Ceriops decandra*, related to an ability to induce antimicrobial activity in mice has been found (Sakagami et al., 1998).

Mangroves are rich in polyphenols (Kathiresan & Ravi, 1990; Ravi & Kathiresan, 1990). A protocol for extraction of black tea from mangrove leaves has been developed (Kathiresan, 1995b). The 'mangrove tea' is rich in theaflavin, the substance responsible for the briskness and colour of the tea. The tea, which shows no mammalian toxicity, can be improved by UV radiation (Kathiresan & Pandian, 1991, 1993; Kathiresan, 1995b).

Levels of chlorophylls and carotenoids are high during summer, flavonoids are high during premonsoon and anthocyanins are high in monsoon (Oswin & Kathiresan, 1994). Moorthy & Kathiresan (1997a) have proposed a physiological grouping of mangrove species based on pigment differences. Phenols and flavonoids in the leaves serve as 'UV-screen' compounds (Moorthy & Kathiresan, 1997b). Hence, mangrove tolerate solar-UV radiation and create a UV-free, under canopy environment (Moorthy, 1995).

Degradation of mangroves

Figure 3 exhibits the possible factors responsible for degradation of the mangrove ecosystem in the study area. Studies of forest structure reveal that timber resources are poor, mainly due to a low diameter of individual trees (3–18 cm), and short canopies (4.8–5.9 m) (Muniyandi, 1986; Kathiresan et al., 1994a). This compares unfavourably with mangroves in South Sumatra (55 cm canopy height), Philippines (25–30 m) and Mexico (17 m) (Pool et al., 1977). Any mangrove in the hurricane belt is said to have low canopy height with low tree diameter. The present study area is affected by frequent cyclones almost every alternate year (Muniyandi, 1986). Cattle grazing and high soil salinity are other factors which affect the forest structure of the area (MSSRF, 1998; Figure 3). All these result in a shrinkage of the total area from 4000 ha at the beginning of 20th century to < 1100 ha at present (Muniyandi, 1986).

The brackish waters, which accumulate in the bowl-shaped mangrove soil substratum during monsoon, turn hyper-saline during summer, ultimately killing or retarding the growth of mangrove seedlings, and those central areas thus become barren after some years (Muniyandi, 1986). This situation is seen in degraded areas at Pichavaram,where the soil salinity goes up to 100 g kg^{-1}(MSSRF, 1998). This problem becomes serious due to poor precipitation and poor free flux of freshwaters (Muniyandi, 1986; Figure 3). The problem can be overcome by flushing the central barren areas with tidal water through the construction of artificial creeks.

Table 4. Potent mangrove extracts showing mosquito-larvicidal, skin- & smoke- repellent and antiviral activities

Mangrove sample	Effective dose	Activity & test organism	Reference
Rhizophora apiculata - stilt root	17 mg l^{-1}	Mosquito larvicidal activity 50% against *Anopheles stephensi*	Thangam & Kathiresan (1988)
Rhizophora mucronata - stilt root	26 mg l^{-1}	50% activity; *Aedes aegypti*	Thangam & Kathiresan (1991)
Avicennia marina - leaf	52 mg l^{-1}	50% activity; *Anopheles stephensi*	Thangam & Kathiresan (1988)
Bruguiera cylindrica - leaf	56 mg l^{-1}	50% activity; *Culex tritaeniorhynchus*	Thangam & Kathiresan (1989)
Rhizophora mucronata - stilt root	76 mg l^{-1}	50% activity; *Aedes aegypti*	Thangam & Kathiresan (1991)
Rhizophora apiculata - stilt root	1 mg cm^{-2} skin area	Skin repellent activity against *Aedes aegypti* up to 70 min	Thangam & Kathiresan (1993b)
Excoecaria agallocha - leaf powder	50% of coil formulation	Smoke repellent activity against *Culex quinquefasciatus*; 56% of mosquitoes not biting; 89% reduction in F_1 mosquito population	Thangam & Kathiresan (1992b)
Acanthus ilicifolius - leaf powder	- do-	Smoke repellent against *Aedes aegypti*; 74% of mosquito not biting; 100% reduction in F_1 mosquito population	Thangam et al. (1992)
Acanthus ilicifolius - root	75 μg ml^{-1}	90% activity *in vitro* against New castle disease virus (NDV)	Premanathan et al. (1993)
- do -	1 mg egg^{-1}	40% embryo protected from NDV	- do -
Rhizophora mucronata - bark	18.5 μg ml^{-1}	50% *in vitro* activity against Vaccinia virus	Premanathan et al. (1994a)
- do -	7.5 μg ml^{-1}	50% prophylactic activity against EMC-Virus	Premanathan et al. (1994b)
- do -	31.25 g kg^{-1} d^{-1}	30% mice protected *in vivo* against EMCV	Premanathan et al. (1994b)
Rhizophora mucronata - leaf	6.0 μg ml^{-1}	50% *in vitro* activity against Semiliki forest virus (SFV)	Premanathan et al. (1995)

Table 4. Continued

Mangrove sample	Effective dose	Activity & test organism	Reference
- do -	31.25 mg kg^{-1} d^{-1}	40% mice protected *in vivo* against SFV	- do -
Rhizophora mucronata - bark	7.61 μg ml^{-1}	50% activity *in vitro* against HIV	Premanathan et al. (1996)
- do -	30 μg ml^{-1}	96.69% of HIV adsorption inhibited	- do -

The Pichavaram area presently suffers from reduction in fishery resources, due to sandbar formation near the river mouth, resisting free flow of tidal waters (along with fish) to the mangrove (Rajendran, 1997; Kathiresan, 1999; Figure 3). Dredging of the river mouth region and afforestation of denuded areas would solve this problem.

Furthermore, is that a large number of plant propagules are not properly dispersed and established (Kathiresan & Moorthy, 1992). This may be attributed to the poor flow of tidal waters from the sea, and can be overcome by dredging of the river mouth. A special programme is required to collect mature propagules from the canopy and plant them in appropriate places.

Up to 12% of the area of mangrove leaves is damaged. Common damage encountered is holes, galls and leaf miner attack in *Avicennia* species, necrotic spots in *Ceriops decandra* and *Rhizophora* spp. and incursions along leaf margins of *Bruguiera cylindrica*. The leaf damage is maximum in *Avicennia*; and is negatively correlated with tannin content (Kathiresan, 1992). A dangerous pest, *Aspidiotus destructor* (Hemiptera, and family – Diaspidiae) larvae and adults damages the seedlings of *Rhizophora* (Kathiresan, 1993).

Mangrove woods are bored by crustaceans and molluscs. Among crustaceans, the spaeromatids (*Sphaeroma terebrans* and *S. annandalei*) are the commonest and most abundant in the study area (Sivakumar, 1992). Ten wood-boring molluscan species also damage the mangrove wood. They include five teredinids viz., *Bankia campanellata*, *B. carinata*, *Dicyathifer manni*, *Lyrodus pedicellatus* and *Teredo furcifera*; and two pholads viz., *Martesia striata* and *M. nairi* (Sivakumar & Kathiresan, 1996). Dead mangrove stumps exhibit higher infestation of wood-borers than live ones. The infested stumps and other trash wood lying in the mangroves provide a perennial source of borer larvae for fresh attack (Sivakumar & Kathiresan, 1996). Besides wood borers, wood fouling marine organisms like bryozoans occur especially in the stilt roots of *Rhizophora* (Nair, 1991).

Conservation and development

The optimum conditions for growth of *Rhizophora* have been studied experimentally. Propagule length, planting depth, soil type, salinity, leachates, pH and light intensity all influence growth (Kathiresan & Thangam, 1989, 1990a; Kathiresan & Ramesh, 1991; Kathiresan & Moorthy, 1993; Kathiresan et al., 1993, 1995b, 1996b). Hormones and other chemicals (e.g. NAA, IBA, IAA, phenolics, GA_3, methanol, boric acids, triacontanol) enhance root growth in *Rhizophora* and *Avicennia* propagules (Kathiresan & Thangam, 1990b; Kathiresan & Moorthy, 1992a, 1994a,b,c,d; Kathiresan et al., 1990, 1994c, 1996c). Triacantanol and methanol increase photosynthesis and growth of *Rhizophora* seedlings. These chemicals further increase *in vivo* nitrate reductase activity, growth of roots and shoots, the protein and energy contents of leaves and roots, the content of chlorophylls and carotenoids in leaves, and the amount of chlorophyll present in Photosystem I and II and in the light harvesting complex of the chloroplasts (Moorthy & Kathiresan, 1993; Kathiresan & Moorthy, 1994a; Kathiresan et al., 1996a). The seedlings easily get adapted in natural soil habitats, when planted after chemical treatments.

Performance of mangrove seedlings has been studied under natural conditions. *Rhizophora apiculata* seedlings grow more rapidly in lower than in upper intertidal zones. Growth is also rapid towards late monsoon and early post-monsoon months, associated with

Figure 3. Possible factors responsible for degradation of mangroves and depletion of fishery resources at Pichavaram.

low salinity and high levels of nutrients (Kathiresan et al., 1996a). Seedlings of *Rhizophora apiculata* exhibit better growth in the estuarine area, rich in potassium (Kathiresan et al., 1994b). Vegetative propagation has been successfully demonstrated to regenerate endangered species of mangrove (Kathiresan & Ravikumar, 1993, 1995b). The effect of effluent from a shrimp pond on shoot biomass of five species of mangroves has been studied and it is suggested that a 70% of diluted effluent is required for growing vigourous seedlings (Rajendran & Kathiresan, 1996). All these investigations have developed the techniques beneficial for raising seedlings of mangroves (Kathiresan, 1995c). Based on these techniques, mangrove plantations are now being established, especially for the endangered species on the degraded coastal areas of Parangipettai and Ariyankuppam, southeast coast of India.

Tissue culture work in mangrove and saltmarsh plants is in progress. Callus induction has been achieved in *Sonneratia apetala* and *Xylocarpus granatum* (Kathiresan & Ravikumar, 1997). *In vitro* multiplication of a saltmarsh plant, *Sesuvium portulacastrum,* has been achieved by axillary bud cultures (Kathiresan et al., 1997). *In vitro* cell culture of this plant synthesizes antibacterial substances in higher quantities than do intact plants, demonstrating the potential of these systems for production of metabolites (Kathiresan & Ravikumar, 1997). Cell protoplast fusion technology may allow to transfer salinity-tolerance from mangrove plants to non-salt tolerant species (Swaminathan, 1991).

Concluding remarks

The Pichavaram mangrove ecosystem has been extensively studied over three decades, but now it is noted for the problems that arise due to anthropogenic pressures and coastal ecological changes. The salinity may likely increase due to increasing of temperature, poor precipitation and poor flushing of mangrove soil by tidal waters. This is indicated by 1. luxuriant growth of salt-marsh succulent plants like *Suaeda* spp., in the core mangrove areas (MSSRF, 1998), 2. lowering of terrestrial gastropod populations (Balasubrahmanyan, 1994) and 3. formation of xerophytic vegetations on dry saline sand flats, in the interior areas of mangrove islets which do not have access to tidal water (Muniyandi, 1986). Figure 3 reveals that poor supply of seawater and freshwater, as well as their mixing has much influence on the mangrove ecosystem and its fishery resources. This aspect deserves immediate attention and intensive studies especially for (1) hydrodynamic fluxes and (2) migration of faunal species from neritic and fresh waters to the mangrove habitat. Other aspects like cattle grazing, illegal felling, overfishing etc. require management with local community participation.

The *Rhizophora* species, which have the best ability to resist solar UV-B radiation, may be selected for vegetating the tropical coastal environment where the incidence of solar UV-B is a growing threat (Moorthy, 1995; Moorthy & Kathiresan, 1997a,b). The mangrove seedlings may be transplanted during the months of low salinity to suitable areas like low intertidal areas rich in potassium, after raising them in nurseries (Kathiresan et al., 1994b, 1996a). Studies are in progress to test the efficacy of mangroves as sources of life saving drugs and other high value products. In this regard, rare forms of microbes from mangroves deserve more studies.

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