Sediment–nutrient dynamics in selected Indian mangrove ecosystems – land use and climate change implications

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Abstract The eastern coast of India harbours a number of mangrove forests, which are now under stress due to climate change-induced sea level rise; sea level is steadily increasing at a rate of 9–12 cm year^{-1}. Current projections for sea level rise are about 0.4–0.9 m; this will have a devastating effect on Indian mangroves. There is significant variability in local C, N and P chemistry, and the accumulation and export of these nutrients are due to changes in land use patterns and rising sea level. Seasonal variations control sediment-associated trace metals, organic C, total N, and total P, and reflect spatial and temporal differences in sedimentary organic production. Population dynamics of polysaline species have changed drastically due to varying inputs of autochthonous sediments from land and salt water inundation/intrusion, mainly at the seaward ends of the mangrove forests. The nutrient-rich sediments create a breeding and fishing ground for various ecologically and economically important species. In these mangroves, sediment-associated trace element concentrations are also increasing as a result of anthropogenic inputs, and influence the biogeochemistry of the ecosystems. An effort has also been made to assess the trace metal concentrations in the three east coast mangroves of India (Sundarbans, Bhitarkanika and Pichavaram) to define the drivers for variations in metal distribution.

Key words mangrove; metals; nutrients; climate change

INTRODUCTION

Mangroves represent highly dynamic and fragile ecosystems. The potential role of mangrove ecosystems as sinks for anthropogenic contaminants in tropical and subtropical areas has been widely recognized (Lin & Dushoff, 2004). Sediments are important carriers of nutrients and trace metals in the hydrological cycle, thus controlling the productivity of the ecosystem (Szefer *et al.*, 1995). According to the Intergovernmental Panel on Climate Change (IPCC), India is amongst the 27 countries that are most vulnerable to sea level rise caused by global warming (IPCC, 2007). The east coast of India harbours ~90% of the total mangrove forest cover for the whole country; therefore, an attempt has been made to define the driving force(s) behind sediment–nutrient dynamics in these ecosystems (Sundarbans, Bhitarkanika and Pichavaram). Contemporaneously, the impacts of climate variability and land-use change on nutrient behaviour and dynamics were also evaluated.

STUDY AREA

Sundarban Mangrove Forest is located (21°32′–22°40′N; 88°05′–89°00′E) in the Ganges-Brahmaputra River system (Fig. 1). It has been declared a World Heritage site for its rich and diverse flora and fauna (Ramanathan *et al.*, 2008). The estuary also receives raw sewage sludge from Kolkata (present name for Calcutta), through the Bidhyadhari River. Sundarban is experiencing an average sea level rise of 3.14 mm year^{-1}, in conjunction with the submergence of its islands and mangrove forests (Gopal & Chauhan, 2006).

Bhitarkanika Mangrove Forest (20°4′–20°8′N; 86°45′–87°50′E) is located in the Mahanadi River delta (Fig. 1). The Bhitarkanika ecosystem flourishes in the deltaic region formed by the rich alluvial deposits of the Brahmani and Baitarani rivers. Bhitarkanika mangrove water and sediment quality are impacted by reduction in freshwater input and industrial discharges (Chauhan *et al.*, 2008).

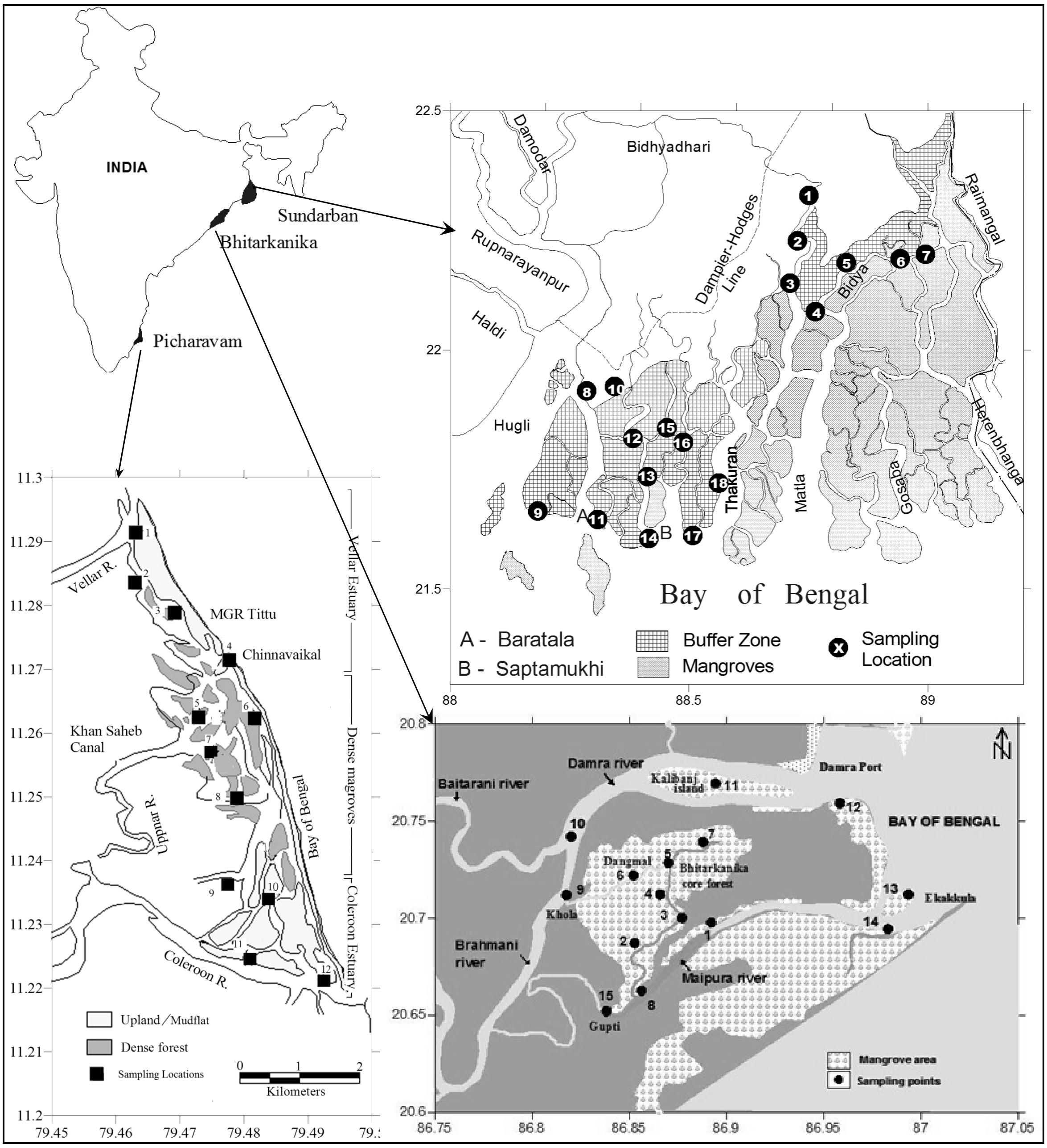

Fig. 1 Map showing Sundarban, Bhitarkanika and Pichavaram mangrove ecosystems.

The Pichavaram Mangrove Forest (11°23′–11°30′N; 79°45′–79°50′E) is located between the Vellar and the Coleroon estuaries of the Cauvery delta along the southeast coast of India (Fig. 1). With an area of 11 km^2, Pichavaram consists of 51 islets; 50% of the total land area is covered by forest, 40% by urban waterways (for fishing), and the rest is filled by mud and sand flats (Krishnamurthy & Jayaseelan, 1983). This formerly pristine ecosystem has been degraded as a result of rapid industrial growth (Subramanian, 2004).

MATERIALS AND METHODS

Eighteen surface water samples, representing the entire ecosystem, were collected from Sundarban, 12 samples were collected from Pichavaram, and 15 samples were collected from

Bhitarkanika. Sampling locations were based on land use, vegetative cover, anthropogenic inputs, and geomorphologic features.

In Sundarban, samples S3, S4, S5, S6, S7, S13, and S14 were collected from pristine areas whereas samples S1, S2, S8, S9, S10, S11, S12, S15, and S16 were collected from anthropogenically impacted areas. In Bhitarkanika, samples S1–S5 represent river-estuarine environments, samples S6–S10 are from dense mangrove regions, and the rest are from purely estuarine regions. In Pichavaram, samples S1, S2, S3 and S4 were collected from the Vellar region; S5, S6, S7, S8 and S9 are from the dense mangrove forest region, and samples S9, S10, and S12 are from the Coleroon estuary. Samples were stored at 4°C on ice, until nutrient and metal analyses were performed using standard analytical procedures. In the laboratory, sediment samples were air dried and washed with MilliQ water to remove halides. The halide-free samples were analysed for total carbon (TC) using an ELTRA (CS 1000) CS analyzer. Organic matter was removed, prior to analyses for inorganic carbon (IC) using a 30% v/v H_2O_2 treatment (Jackson, 1973). Organic carbon (OC) was estimated by the difference between TC and IC (OC = TC – IC). Total nitrogen (TN) and total phosphorus (TP) were determined by Kjeldahl analyses (Anderson & Ingram, 1993). Sediment-associated trace metals were solubilized with *aqua regia* (Sterckman & Gomez, 1996), and determined by Atomic Absorption Spectrophotometry (AAS).

RESULTS AND DISCUSSION

Sundarban mangrove

The Sundarban mangrove provides an average of 6000 t ha^{-1} of mangrove litter that produces a huge amount of organic carbon (OC) for the whole ecosystem. High levels of OC (dissolved and solid phase) are observed in the pristine areas (dense mangroves; Fig. 2(a)). The sediments associated with dense mangroves display high OC concentrations due to biological productivity. Land-use patterns associated with maximum disturbance show low levels of OC (Choudhary *et al.*, 2005). Despite considerable anthropogenic activities in the buffer zones, OC mimics the core/pristine areas. The distribution of total nitrogen (TN) is controlled by sediment grain size, with the highest concentrations associated with the finer fractions. As a result, sediment-associated nitrogen levels appear to be weather-related, with concentrations declining through the pre-monsoon to post-monsoon to monsoon (Fig. 2(b)). Generally, in the tropical coastal ecosystems P is the limiting nutrient, and significant spatial variability is observed in total sediment-associated phosphorus (TP) (Fig. 3). TP values in buffer zone sediments are significantly higher and show increasing seaward trends. Overall, pristine zone-sediments contain high nutrient levels that have autochthonous sources. Changes in land use and climatic influences alter nutrient concentrations that, in turn, affect biological productivity. Metal concentrations occur in the following declining order of concentration, with little variation: Iron (Fe) > Manganese (Mn) > Lead (Pb) > Zinc (Zn) > Chromium (Cr) = Nickel (Ni) > Cadmium (Cd) (Table 1). Relatively high metal levels (Table 1) are associated with natural sources (weathering) and the degradation of organic matter (Lacerda, 1997), followed by anthropogenic inputs from industrial effluents (Sarkar *et al.*, 2007), runoff from agricultural lands (Lambert *et al.*, 1981), waste discharges, and from the use of low quality leaded fuel.

Tidal rivers in the Sundarban Mangrove Forest are complex, and characterized by high salinity due to climatic changes which resulted from the reduction of freshwater inputs (Ramanathan *et al.*, 2008). Freshwater dominance is isolated towards the eastern part of wetland, therefore in many places freshwater species (*Heritiera fomes*) have been superseded by saline-dominant species (*Rhizophora* sp., *Avecinnia* sp.) (Kathiresen, 2004; Gopal & Chauhan, 2006). Continuously shifting river courses cause degradation of mature mangrove forests and have a tremendous impact on vegetative cover and biodiversity. Further, the choking of waterways due to siltation leads to the formation of back swamps. As a result hydrology in this area is dominated by rainwater rather than riverine inputs, causing the replacement of mangrove species by swamp species (Gopal & Chauhan, 2006).

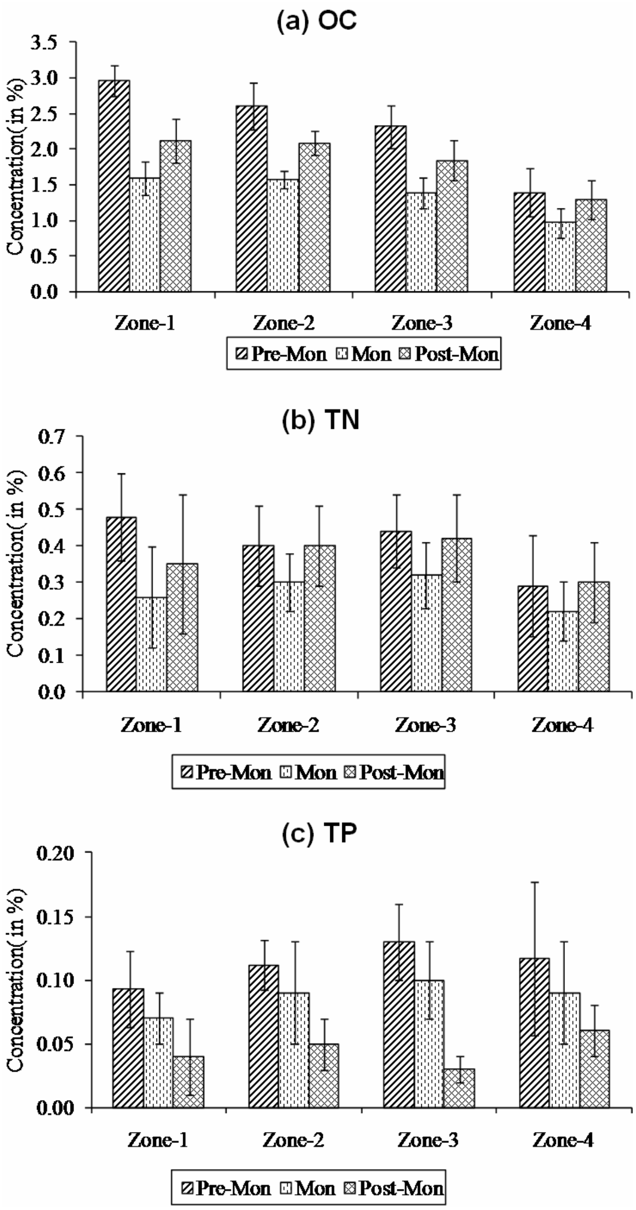

Fig. 2 Zonal variation in sedimentary nutrients: (a) organic carbon (OC), (b) total nitrogen (TN) and (c) total phosphorus (TP) in the Sundarban mangroves. Zone 1 represents the samples collected from the pristine region whereas zone 3 respresent the land use with maximum disturbance.

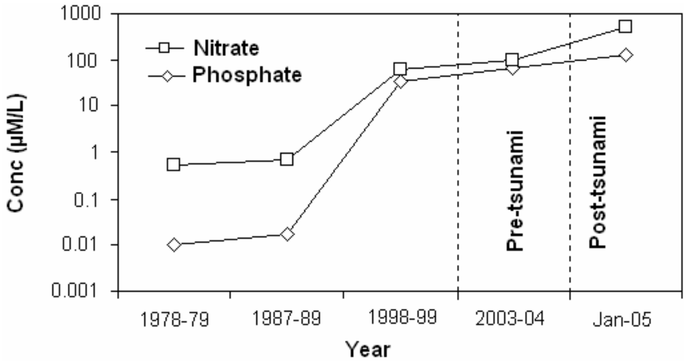

Fig. 3 Decadal changes in the major nutrients in the Pichavaram mangrove environment (source: Ranjan *et al.*, 2008).

Table 1 Sedimentary heavy metal distribution (Min–Max (avg. ±SD) mg g^{-1}) in the mangroves along the east coast of India.

	Sundarban (n = 18)	Bhitarkanika(n = 15)	Pichavaram(n = 12)
Fe	23–91 (50.5 ± 18.9)	20–56 (29.5 ± 11.1)	33–91 (49 ± 22)
Mn	0.2–9.5 (2.8 ± 2.4)	0.03–0.25 (0.16 ± 0.03)	0.03–0.45 (0.12 ± 0.14)
Zn	0.1–2.0 (0.5 ± 0.4)	0.02–0.17 (0.09 ± 0.05)	0.03–0.15 (0.049 ± 0.034)
Cr	0.0–0.9 (0.3 ± 0.12)	0.35–0.38 (0.36 ± 0.3)	0.3–1.34 (0.53 ± 0.27)
Cd	0.0–0.7 (0.2 ± 0.08)	0.1–0.49 (0.29 ± 0.07)	0.19–0.80 (0.29 ± 0.25)
Ni	0.1–0.6 (0.3 ± 0.11)	0.03–0.04 (0.035 ± 0.03)	0.01–0.03 (0.01 ± 0.008)
Pb	0.1–2.2 (1.0 ± 0.6)	0.37–0.41 (0.39 ± 0.12)	0.07–0.19 (0.14 ± 0.036)

Bhitarkanika mangrove

Weather plays a significant role in controlling environmental conditions in the Bhitarkanika mangrove forest. Soil redox potential is much more reduced during the monsoon period relative to the post-monsoon period. Soil salinity varies from 2.4 dSm^{-1} during the monsoon to 42.6 dSm^{-1} during the pre-monsoon; the monsoon-related decline in soil salinity results from increasing freshwater supplies. The higher average salinity during the pre-monsoon indicates saltwater intrusion due to low riverine flow in conjunction with increasing evapotranspiration. Salinity exerts a direct and indirect control over nutrient availability (Dittmar & Lara, 2001; Ragueneau *et al.*, 2002). Agricultural runoff and aquacultural effluents are the main sources for higher concentrations of nitrate and phosphate during the monsoon.

During the pre-monsoon, sediment-associated OC ranges from 0.7% (site S10) to 1.5% (S9), with an average value of 1.0%. Despite restoration efforts, Site S10 is the most degraded in the system and has the lowest number of new *Rhizophora*. During the monsoon, OC varies widely from 0.5 (S10) to 1.7% (S6), with an average value of 0.9%. During the post-monsoon, OC varies from 0.5% (S7) to 1.4% (S6), with an average value of 0.9%. High OC levels are observed at S6 due to a substantial allochthonous carbon supply through river runoff. During the pre-monsoon, total nitrogen ranges from 0.07% (S7) to 0.10% (S3) with an average of 0.09%. Sediment-associated nitrogen varies from 0.05% at site S2, to 0.09% at site S4, with an average of 0.07%, whereas during the monsoon, it ranges from 0.06 to 0.15%.

Generally, low average C:N ratios were observed in the post-monsoon . The C:N ratio ranges from 9 to 17 during the pre-monsoon, 6 to 21 in the monsoon season, and 6 to 14 in the post-monsoon. The high pre-monsoon and monsoon-related C:N ratios suggest that most sediment-associated organic matter is derived from mangrove litter (Fleming *et al.*, 1990). The high C:N ratio of mangrove litter (e.g. leaves, wood), high rates of bacterial production (Alongi *et al.*, 1992), and low NH_4^+ fluxes across the sediment–water interface (Kristensen *et al.*, 1988) appear to indicate that the immobilization rates of nitrogenous organic compounds may be high in mangrove sediments. Major losses of nitrogen from the system occur via tidal flushing and, to a lesser extent, from denitrification.

The high N:P ratios appear to indicate that sediments supply more nitrogen than phosphorus. Further, the low C:N ratios suggest nitrogen enriched conditions have inorganic origins and that inorganic nutrient sources prevail during the post-monsoon. During the post-monsoon, high chlorophyll-*a* concentrations in mangrove creek water could be due to the delayed sinking of organic material derived from cyanobacterial blooms; these blooms decrease the C:N ratio (5.8) and increase the N:P ratio (up to 12) from sediment-derived nutrients. TP in surface sediments averages 430 µg g^{-1} during the pre monsoon whereas during the monsoon and post-monsoon it averages 360 µg g^{-1}. Lower riverine flow, less rain and higher rates of evapotranspiration resulted in higher concentrations of TP during the pre-monsoon.

High concentrations of heavy metals (i.e. Fe, Mn, Cr, Cd, Zn and Pb) are found in areas affected by anthropogenic activity, particularly at the entry points to the mangrove areas of the Brahmani and Baitarani rivers (Table 1). Heavy metal concentrations are lowest in regions with dense mangroves. The impact of pollution on river chemistry is most evident in the Brahmani River where high concentrations correspond with high discharges from upstream industrialized areas.

Pichavaram mangrove

The Pichavaram mangrove forest, located along the southeast coast of India, represents a case study for mangrove degradation due to aquaculture. During the 1970s, there were no aquaculture ponds in the area, whereas by 1984, there were 4 km^2, and by 1996 there were 7 km^2 (Kathiresan, 2000; Cho *et al.*, 2004).

Table 1 contains sediment-associated metal concentrations for the Pichavaram mangrove forest. The Vellar and Coleroon rivers display the highest concentrations for nearly all the heavy metals evaluated in this study. The metals appear to have an anthropogenic source (domestic sewage and agricultural runoff) (Ranjan *et al.*, 2008a). The heavy metal concentrations are low in the mangrove regions. The biogeochemical processes in this ecosystem are governed by the heavy input of sediments and anthropogenic discharges from these two rivers, which pass through densely populated industrial cities and, in addition, carry fertilizer, heavy metals and pesticides from the upstream reaches of the basin (Ramanathan *et al.*, 1999).

As noted, there has been a rapid increase in the number of aquaculture ponds during the past 40 years (Cho *et al.*, 2004). Recently, there also has been extensive fertilizer use (DAP, Di-Ammonium-Phosphate) in the adjoining agricultural lands (Ramanathan *et al.*, 1999). As a result, agricultural waste is being transferred to the estuarine mangrove complex, and there has been a significant increase in phosphate and nitrate concentrations during the past few years (Fig. 3).

In Pichavaram sediments, the average concentration of TC and TOC is 14.5% and 10.2%, respectively; further, total nitrogen and phosphorous average 0.9%, and 0.8%, respectively (Ranjan *et al.*, 2008). The elevated concentrations of OC are due to the presence of fine-grained sediments (Ramanathan, 1997) and from the inherent biological productivity within the mangrove area. The dense mangrove sediments are finer-grained than adjacent estuarine sediments; as a result, mangrove sediments have a higher sorptive capacity for organic compounds and thus, contain more TC and TOC (Ranjan *et al.*, 2008). Dissolved OC from anthropogenic activities, in conjunction with internal biogeochemical processes as well as simple human pressure, is ultimately scavenged by the sediments (Subramanian, 2004; Prasad & Ramanathan, 2008) and results in their increased nutrient loadings.

TN is higher in mangrove-associated sediment than in Vellar and Coleroon-dominated estuarine sediment, across all grain sizes (Ranjan *et al.*, 2008). TP in the Pichavaram sediments ranged from 450 to 550 $\mu g\ g^{-1}$ and iron bound phosphorus (Fe-P) is the dominant chemical fraction in surface sediments (Prasad & Ramanathan, 2010). Sedimentary chemical fractions, exchangeable (Exch-P), iron bound (Fe-P), and organic bound phosphorus (Org-P) are generally considered as potentially bioavailable in the coastal wetland (Andrieux-Loyer & Aminot, 1997). High levels of bioavailable P in the core mangrove zone primarily are due to retention, cycling and mineralization of TP. Bioavailable P accounts for 53–61% of the P in mangrove sediments; however, 39–47% of the sediment-associated P is unavailable for biological uptake (Prasad & Ramanathan, 2010). This would indicate that the intertidal mangrove sediments are an important autochthonous source of P for the ecosystem, whereas in the estuarine zone, allochthonous sources of P are dominant. The C:N and N:P ratios in Pichavaram mangrove sediments are low, suggesting that labile organic matter is high. This is likely due to inputs of aquacultural effluents, agricultural runoff, and domestic sewage (Purvaja & Ramesh, 2000).

Mangrove seedlings require low salinity; however, growth requires higher, but limited salinities if the growth is to be maximized (Kathiresan, 2000). The Pichavaram mangrove is affected by cyclones occurring almost every other year. Cattle grazing and high soil salinity are major factors which affect the local forest structure. Seasonal fluctuations in salinity are regulated by the influx of freshwater during the monsoon season, and neritic water in non-monsoonal periods. In summer, hypersaline water that has accumulated in a bowl shaped-lagoon increases the local soil salinity up to 100 g kg^{-1} (Kathiresan, 2000). Normally, during the monsoon, hypersaline water is diluted with rainwater and influences biological productivity. However, this does not appear to be occurring in Pichavaram due to reductions in upstream freshwater sources. As a result of all these factors, the mangrove forest has shrunk from a total area of about 4000 ha (beginning of the 20th century) to <1100 ha (Kathiresan, 2000).

Climate change perspective

Climatic factors in the region, such as temperature, humidity, and precipitation, number of rainy days, regular wind flow, radiation, and the flow of freshwater, exert the most impact on the development and succession of mangroves. A significant proportion (40%) of utilized carbon is ultimately transferred back to the environment via litter fall. Worldwide nutrient balance studies have shown that the litter fall is trapped and eventually buried in mangrove sediments (Alongi, 2009). Stable isotope studies have confirmed that nearly 100% of the sediment-associated carbon in mangrove forests originates in the mangrove biomass itself; this carbon can accumulate, and reaches very high concentrations (Risk & Rhodes, 1985). Sediment erosion exports large amounts of carbon to adjacent coastal areas. Since a proportion of this carbon still has a great oxidative capacity, substantial oxygen consumption is expected when this eroded material reaches oxygen-rich coastal waters (Emeis, 1987). Theoretical modelling of past relative sea level increases (RSLR) predicts the eutrophication of coastal waters (Emeis, 1987). Eutrophication also results in increasing nitrification, nitrate enrichment of outwelling waters, and additional coastal eutrophication. The pulses of oxidation-erosion expected under conditions created by RSLR, also may lead to the acute release of accumulated trace metals which could threaten the mangrove food chain, declining mangrove forests, and increases in the decomposition of sediment-associated organic matter. Several studies have demonstrated that the metal retention capacity of mangrove sediments is adversely affected by increasing salinity (e.g. Tam & Wong 1999). Thus, it is anticipated that mangrove ecosystems would also deteriorate as a result of increasing metal contamination from anthropogenic sources, and changing land use patterns within the basin.

Increasing sediment temperature may lead to increases in nutrient recycling and regeneration rates. The long-term effect of these factors on microbial activity and nutrient cycling is difficult to predict. In addition, due to the increasing influence of seawater as sea level rises, the source of organic matter will shift from terrestrial to marine. This shift affects carbon preservation and carbon burial, because marine organic matter is more susceptible to degradative changes than terrestrial organic matter (Hedges *et al.*, 1988).

CONCLUSIONS

The mangrove ecosystems along the east coast of India are vulnerable to rapid changes in land-use, as well as to climate-induced sea level rises. Sediment derived from both fluvial and marine sources plays a significant role in mangrove nutrient dynamics. Studies have shown that these mangrove ecosystems have displayed increases in autochthonous nutrient production, accumulation, and export due to changing land use patterns and climate-induced sea level rises. Climate variations also play a substantial role in the distribution of major nutrients such as C, N and P. Polysaline species populations vary with respect to the differential inputs of saline water and autochthonous nutrient rich-sediments. The sediment also shows an increasing trend in macro and micro nutrients due to anthropogenic inputs. All these factors appear to be detrimental to the survival of local flora and fauna, as well as biological productivity.

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