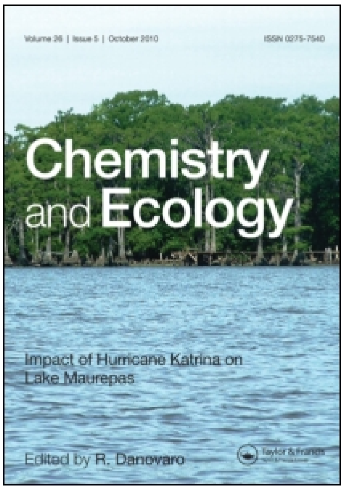

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Natural and Anthropogenic Effects On Phytoplankton Primary Productivity in Mangroves

R. Purvaja[a]; R. Ramesh[a]
[a] Institute for Ocean Management, Anna University, Chennai, India

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NATURAL AND ANTHROPOGENIC EFFECTS ON PHYTOPLANKTON PRIMARY PRODUCTIVITY IN MANGROVES

R. PURVAJA and R. RAMESH*

Institute for Ocean Management, Anna University, Chennai 600 025, India

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Spatial and temporal variations and the factors influencing primary production have been studied in three different mangrove waters (Pichavaram, Ennore Creek and Adyar Estuary) of South India characterised by different anthropogenic impacts. The gross primary productivity in the unpolluted Pichavaram mangrove was 113 $g\,C\,m^{-2}\,yr^{-1}$ exhibiting natural variability with the environmental forcing factors. Human activities have elevated primary productivity in the Ennore Creek mangrove (157 $g\,C\,m^{-2}\,yr^{-1}$) primarily through the direct discharge of fertilizer effluents. By contrast, a combination of domestic and industrial effluent discharges into the Adyar Estuary mangrove has considerably reduced phytoplankton primary productivity (83 $g\,C\,m^{-2}\,yr^{-1}$). The Redfield N : P ratio varies from 0.96 N : 1P at Ennore Creek, 1.75N : 1P at Adyar Estuary to 15.2 N : 1P at Pichavaram mangroves. This suggests that the Pichavaram mangroves represent a well equilibrated ecosystem with N : P ratio close to steady-state values in contrast to the anthropogenically altered mangrove ecosystems studied. Results show a significant temporal variability in nutrient concentration in the three mangrove areas. Distinct differences in nutrient concentrations between the dry and the wet seasons have been observed.

Keywords: Phytoplankton primary production; nutrients; anthropogenic influence; N : P ratio and mangrove waters

1. INTRODUCTION

Coastal ecosystems such as mangroves act as buffer zones for the transformation and transport of nutrients from land to the coastal zone

*Corresponding author. e-mail: ramesh@annauniv.edu.in

(Robertson, 1993). They serve as the final reservoirs of natural and anthropogenic organic matter and nutrients derived from land by the rivers and through the direct input of sewage and other wastes. These coastal ecosystems also sequester the carbon and nutrients (N and P) from the atmosphere at rates in excess of those occurring in these ecosystems. Smith and Mackenzie (1987) point out those coastal ecosystems can only be met heterotrophic systems if the liberated carbon dioxide is not subsequently consumed by photosynthesis. Photosynthesis is fuelled by nutrients and therefore the nutrient load of a river is a decisive factor in determining whether its plume will be met heterotrophic or autotrophic. The relevance of this sink can be estimated by scaling the anthropogenic inorganic nutrient inputs according to the Redfield Ratio ($C_{106} : N_{16} : P_1$). Studies on primary productivity in mangrove waters in India are very sparse and have been carried out only at a few selected mangroves (Krishnamurthy *et al.*, 1975; Pant, 1985).

The literature is also generally weak on the effect of sewage effluent on mangrove ecosystems (Smith and Mackenzie, 1987). In a review on the effects of nutrients on mangroves, Boto (1992) noted that mangrove productivity may be limited by phosphorus, nitrogen and salinity and suggested that the addition of these and fresh water may increase productivity. Wong *et al.* (1995) examined the ecological impact of sewage discharges to the mangrove wetland. Tam and Wong (1996) tested the mangrove soils for the retention of nutrients from wastewater. While different soils retained nutrients at different rates, the wastewater borne nitrogen and phosphorus were mostly concentrated in the upper 1 cm of the soil, with very little downward percolation, suggesting that the capacity of the mangrove soils in immobilising nutrients was very high. Boto (1992) calculated that mangroves, in general, can sustain the input of $300\,kg\,N\,ha\,yr^{-1}$ and $30\,kg\,P\,ha\,yr^{-1}$ and conversely one hectare of mangrove could accept $\sim 5000\,m^3$ of good secondary effluent each year. He further suggested that the effluent should be added to the upper intertidal zone to permit nutrient uptake by mangrove soils, rather than into the waterways, where the nutrients would increase the algal production and correspondingly oxygen depletion. Wong *et al.* (1995) examined the ecological impact of sewage discharges to a mangrove wetland. Their preliminary results indicate that a discharge of $2600\,m^3$ of municipal wastewater to an area of 0.18 ha of mangrove did not determine any apparent impact on plant growth. The soils and plant leaves were not changed in terms of nutrient content but by the discharged sewage. Tam and Wong (1994 and 1995) demonstrated that mangrove soils were good traps to immobilize wastewater-borne phosphorus but were less efficient in retaining nitrogen from wastewater.

Thus, in the framework of current concern developed for the evaluation of future global environmental change, it is of primary interest to evaluate influence of the various causes of high primary

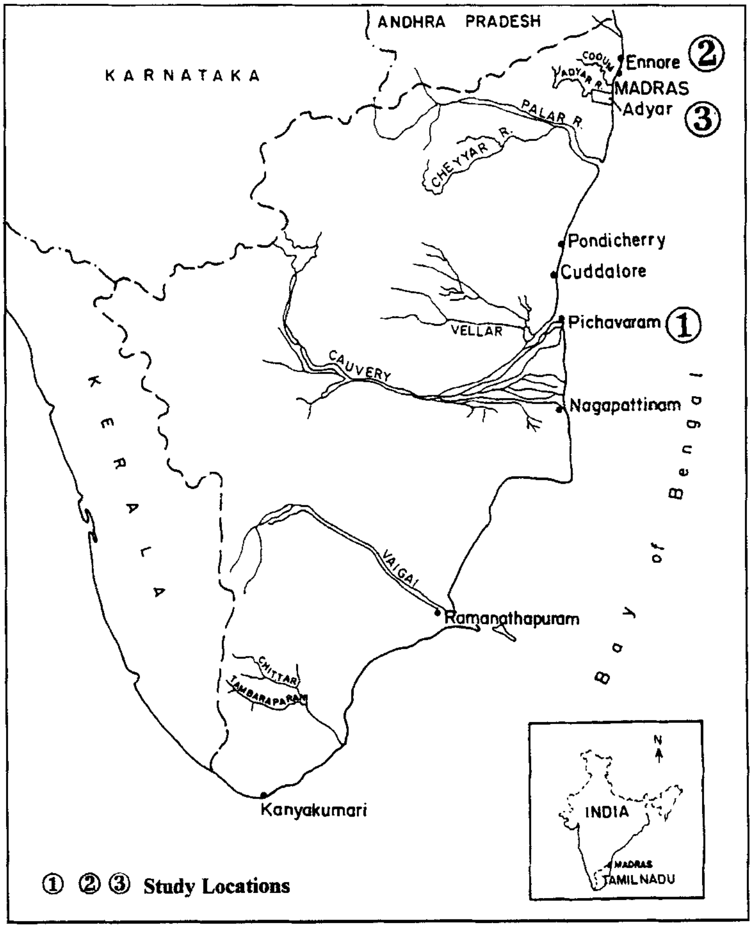

FIGURE 1 Map of the study area: 1. Pichavaram Mangroves; 2. Ennore Creek Mangroves; 3. Adyar Estuary Mangroves.

productivity in the mangrove ecosystems. It is especially important to estimate the influence of anthropogenic activities on the modification of natural primary productivity levels in these ecosystems. The study focuses on phytoplankton primary productivity in natural (Pichavaram) and anthropogenically altered (Ennore Creek and Adyar Estuary) mangrove ecosystems of South India (Fig. 1). Several environmental factors such as light penetration, oxygen and nutrient availability and human induced factors that are known to influence primary productivity have been studied.

2. STUDY AREA

The Indian peninsula harbours some of the thickest mangrove swamps in the world, located in the alluvial deltas of rivers such as the Ganges, Mahanadi, Godavari, Krishna and Cauvery, with a majority (80%) along the east coast of India. In this study, luxuriant mangroves along the Cauvery delta (Pichavaram) and sparse mangroves along the Chennai basin (Ennore Creek and Adyar Estuary) have been studied (Fig. 1), to highlight the changes in nutrient biogeochemistry. The Pichavaram mangroves are located ~225 km south of Chennai city on the south-east coast of India (Lat. 11° 27′ N and Long. 79° 47′E) covering an area of 1400 ha. The mangrove area is traversed by a large number of channels and creeks, which connect the Coleroon Estuary in the south and the Vellar Estuary in the north. Semi-diurnal tides flush this ecosystem with a tidal amplitude of 0.5 to 1 m. Apart from the flushing of neritic waters from the Bay of Bengal, the direct entry of fresh water is through the Coleroon and Vellar rivers and the primary drainage channel is the Khan Sahib Canal. The mangrove vegetation is represented by *Rhizhophora sp.*, *Avicennia sp.*, *Excoecaria sp.*, *Bruguiera sp.*, *Ceriops sp.* Human interference to this ecosystems has been minimal; although tree felling, pollution through agricultural waste discharges and a recent spurt in aquaculture activities are threatening the pristinity of this ecosystem.

Similar to the Pichavaram mangroves, the mangroves along the Chennai basin are influenced by the north-east monsoon. The intertidal margins of the Ennore Creek (Lat. 13° 30′ N and Long. 80° 15′E) and

Adyar River (Lat. 13° N and Long. 80° 15′E) are characterized by small patches of mangrove vegetation and is highly degraded due to severe human intervention. The mangroves cover an area of 70 ha and 48 ha respectively. The mangrove vegetation at both Ennore Creek and Adyar Estuary are dominated by *Avicennia marina* although patches of other shrubs such as *Suaeda* are not uncommon at Ennore Creek. The Ennore Creek area is a region with immense industrial activity specializing in the production of fertilizers, chemicals and dyes and has an assorted integration of other large and small scale industries. The untreated industrial effluents are discharged directly into the Creek area. In the Adyar Estuary, the dominance of domestic effluents, coupled with the intense usage of the river for laundry, contributes significantly to the organic pollution of this waterway.

3. SAMPLING AND ANALYSES

Sampling of surface water was carried out throughout the year (January to December, 1993) on a monthly basis at Pichavaram, Ennore and Adyar mangroves [$n = 5$]. Surface water samples (1 litre) were collected in polyethylene bottles for the determination of various physico-chemical and biological factors. Water samples were maintained at 4°C in ice boxes in the field and were immediately filtered through a 0.45 μm filter (Sartorius, cellulose-nitrate type) on arrival to the laboratory, within 24 hours of sampling. The filtered samples were then analyzed for nutrients (NO_3^{-2}, NO_2^-, NH_4^+, PO_4^{-3}, total dissolved phosphorus [TDP] and H_4SiO_4) using standard procedures (Standard Methods for Water and Waste Water Analysis, 1985). *In situ* measurements of pH, conductivity [EC], water temperature and total dissolved solids [TDS] were carried out, see Table I, using a Metler portable field laboratory kit, after calibration with appropriate standards. Water samples were fixed with manganous sulfate and alkaline iodide for the analysis of dissolved oxygen using the Winkler method. In addition, a light and a dark Biological Oxygen Demand [BOD] bottle filled with water was suspended in the water column for over three hours to estimate the primary productivity using the light and dark bottle method (Ramesh and Anbu, 1996).

TABLE I Monthly variation of environmental parameters in the mangroves of Pichavaram, Ennore Creek and Adyar Estuary

	Pichavaram				Ennore Creek				Adyar Estuary			
Month	*pH*	*Salinity (ppt)*	*Water temp(°C)*	*TDS (g/l)*	*pH*	*Salinity (ppt)*	*Water temp(°C)*	*TDS (g/l)*	*pH*	*Salinity (ppt)*	*Water temp(°C)*	*TDS (g/l)*
Jan.	7.9	20.80	29.0	30.9	7.5	15.2	30.0	26.2	7.2	18.1	29.0	26.4
Feb.	6.8	21.30	32.0	30.6	7.2	15.8	32.5	26.9	6.7	5.50	31.0	15.2
March	7.6	25.20	29.0	32.5	7.4	26.4	31.0	29.0	7.5	20.1	30.5	29.6
April	8.4	26.30	28.0	34.8	8.3	30.2	32.0	33.1	7.3	24.6	31.0	34.7
May	7.4	32.80	28.0	35.1	7.3	33.5	32.5	33.5	7.5	32.6	32.0	34.9
June	6.9	23.60	29.0	34.3	6.4	34.0	31.0	35.9	6.9	33.2	30.5	35.6
July	7.3	10.80	29.0	23.9	7.2	32.4	30.0	35.1	7.1	18.7	30.0	28.7
August	7.4	18.40	29.0	31.0	7.4	30.3	31.0	33.1	7.1	32.7	29.5	35.2
Sept.	7.6	10.10	25.0	19.8	7.4	33.6	29.0	35.2	6.9	26.4	29.0	31.5
Oct.	8.2	8.70	27.5	17.1	7.5	15.6	29.0	26.7	6.8	12.4	28.5	21.6
Nov.	7.1	9.90	29.0	16.1	7.2	13.8	30.5	20.9	6.7	11.8	29.0	20.5
Dec.	7.2	12.40	24.7	27.9	6.8	24.2	28.5	33.5	7.3	20.8	27.5	29.8
Mean	7.5	18.40	28.2	27.8	7.3	25.4	30.6	30.9	7.1	21.4	29.8	28.7

4. RESULTS AND DISCUSSION

4.1. Seasonal Variation in Primary Productivity

The major primary producers identified in the mangrove ecosystems include: the mangrove macrophytes, the phytoplankton in water, the mangrove epiphytes and the photosynthesizing macro- and micro-organisms in sediments. The aquatic primary productivity characteristics varied appreciably between the three mangrove ecosystems studied (Fig. 2). Primary productivity was maximum in the waters of the Ennore Creek [mean: 0.43 SD $\pm$ 0.021], ranging from 0.14 SD $\pm$ 0.02 $g\,C\,m^{-2}\,d^{-1}$ to 0.84 SD $\pm$ 0.08 $g\,C\,m^{-2}\,d^{-1}$, correlating with the oxygen concentration in the water column. Further, the apparently high rates in productivity in the Creek area is also due to the continuous and direct input of nitrogen and phosphorus effluents from the fertilizer producing units.

A distinct seasonality in phytoplankton primary production has been observed in all the three mangrove biotopes (Fig. 2), typically reaching a peak during monsoon and minimum in post-monsoon season. However, secondary peaks in summer were also recorded in all the locations. The Adyar mangrove ecosystem recorded a lower productivity (0.12 to 0.36 $g\,C\,m^{-2}\,d^{-1}$) even though nutrients were not a limiting factor.

Studies on aquatic primary productivity in Pichavaram mangroves have been carried out by Krishnamurthy *et al.* (1975) with respect to salinity, temperature, dissolved oxygen and chlorophyll-a. Krishnamurthy and Sunderaraj (1973) reported a gross phytoplankton primary productivity of 0.59 $g\,C\,m^{-2}\,d^{-1}$ for the Pichavaram mangroves. In the present study, it ranged from 0.18 to 0.45 $g\,C\,m^{-2}\,d^{-1}$ with an average gross primary productivity of 0.31 $g\,C\,m^{-2}\,d^{-1}$. The decrease in productivity has been nearly two-fold in the past two decades which may be due to: (i) increased turbidity and decreased light penetration and (ii) reduced freshwater inflow and low nutrient availability. It can also be noted that nitrate and phosphate were almost removed from the water column (Fig. 2) highlighting the fact that nitrogen and phosphorus are limiting nutrients in the Pichavaram mangroves. This phenomenon also coincides with a secondary peak in productivity in summer (0.32 $g\,C\,m^{-2}\,d^{-1}$) suggesting that

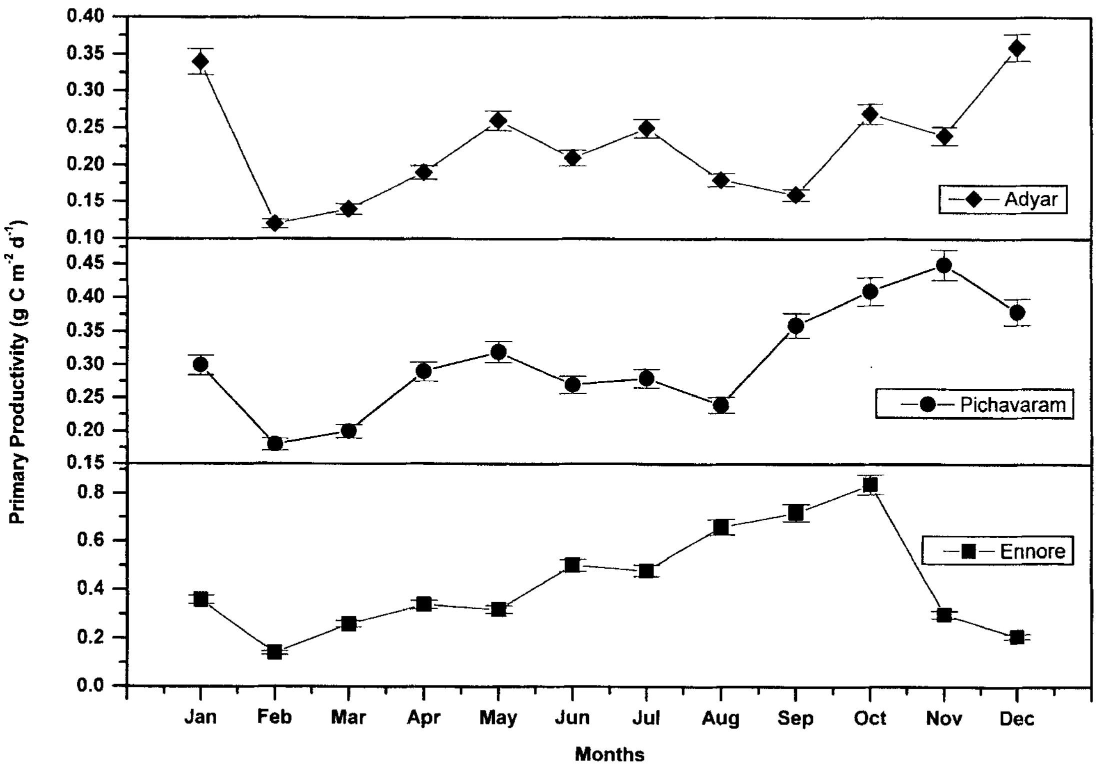

FIGURE 2 Monthly variations in aquatic primary productivity in the mangrove ecosystems of Tamil Nadu.

the phytoplankton are responsible for the removal of nutrients from the surface waters. Thus in all the cases, the seasonal variation in primary productivity is directly proportional to the inflow of fresh water, oxygen and nutrient availability.

4.2. Annual Variation in Primary Productivity

The primary productivity of estuarine and coastal waters is much higher than in open oceans because of greater nutrient supply from rivers and other sources such as agricultural and industrial discharges. Some typical values are 270 $g\,C\,m^{-2}\,yr^{-1}$ for the average coastal environment (Wollast and Billen, 1981) and between 100 and 200 $g\,C\,m^{-2}\,yr^{-1}$ for the estuaries and coastal waters (Williams, 1980). Based on the average annual primary productivity for each mangrove ecosystem studied, the gross primary productivity was calculated. We observed a gross primary productivity of 113.3 $g\,C\,m^{-2}\,yr^{-1}$ for the Pichavaram mangroves, and 157 $g\,C\,m^{-2}\,yr^{-1}$ for the Ennore Creek mangroves which fall within the range observed by Williams (1980) and was significantly lower (82.7 $g\,C\,m^{-2}\,yr^{-1}$) at the Adyar Estuary mangroves. Berner and Berner (1987) report that phytoplankton productivity will be generally higher in polluted areas which have greater nutrient supply. This phenomenon has been observed by us for the Ennore Creek mangroves, where external inputs of nutrients from industrial sources reach the mangrove waters periodically.

4.3. Factors Controlling Primary Productivity

There are several factors that influence or affect phytoplankton primary productivity in mangrove waters. Primary among these, are light penetration, freshwater inflow, dissolved oxygen content, nutrient availability and N : P ratio that is available for phytoplankton productivity.

4.3.1. Light Penetration

In mangrove waters, productivity is limited to the surface layers where light intensity is only sufficient for photosynthesis to occur. Field observations during the post-monsoon season at the Pichavaram mangroves indicate a reduction in freshwater inflow coupled with significant wave action, causing turbidity of the water column. There is hence a decrease in light penetration to the water column, which is reflected in a decrease in primary productivity. At Ennore Creek however, the shallow nature of the Creek (~ 1 m) enables light penetration even to the deeper layers during most part of the year. This helps in maintaining phytoplankton and microphytobenthos productivity at the expense of mangrove productivity. By analogy, continuous addition of domestic effluents enter the Adyar Estuary mangrove waters thereby suppressing light penetration beyond a few millimetres (< 10 mm) of the water column, decreasing the phytoplankton primary productivity significantly.

4.3.2. Oxygen Availability

It can be observed (Fig. 3) that aquatic primary productivity has a strong positive correlation [$n = 5; 0.91; r = 0.99$] with oxygen concentration. In general, regular influx of fresh water coupled with high wave action, usually means that there is ample supply of oxygen in the water column of the mangrove areas. Moreover, the solubility of oxygen in water decreases with increased temperature and salinity, causing oxygen depletion during summer. By contrast, oxygen concentrations were low even during monsoon at the Pichavaram and Ennore Creek waters, resulting from increased organic matter accumulation received by the mangrove ecosystems. In contrast, the Adyar mangrove waters experienced severe oxygen stress through a major part of the year (Fig. 3). High rates of organic matter degradation and the abundance of anaerobic bacteria in the mangrove sediments could have exerted a large oxygen demand on the overlying water column (Ramesh *et al.*, 1997). The continuous input of domestic wastes, see Table II, has further restricted the exchange of interstitial water with the surface, causing stagnation within the mangrove area. It is possible to thus point out that primary productivity is chiefly mediated by oxygen availability in the water column.

4.4. Nutrients in Unpolluted Mangrove Waters

In the Pichavaram mangroves, where external point sources of pollution have not been identified, the availability of nitrogen and

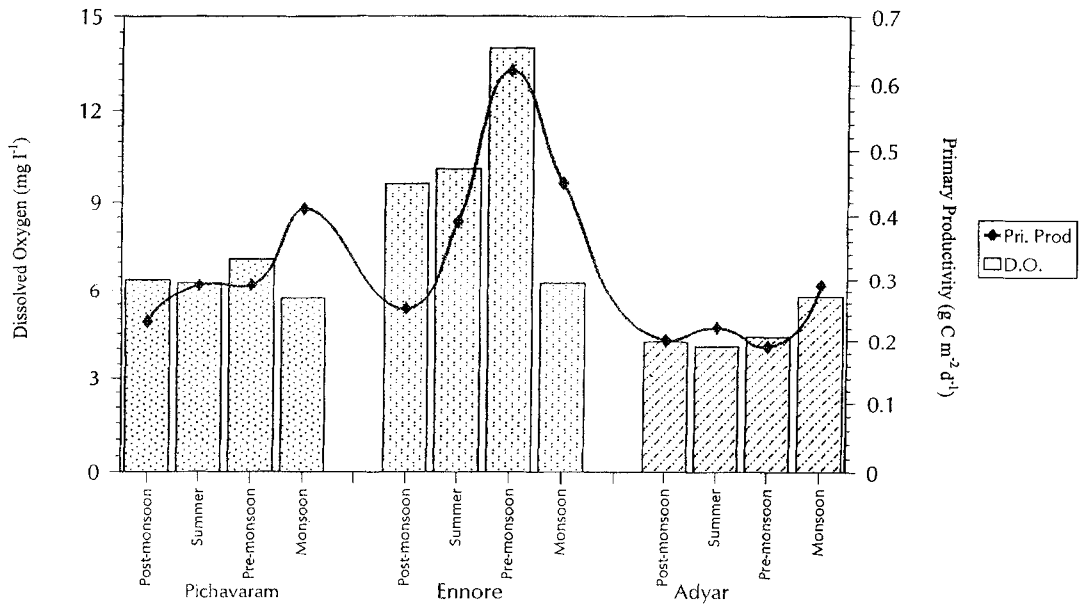

FIGURE 3 Seasonal variations of dissolved oxygen and primary productivity relationship in mangrove waters.

TABLE II Effluent discharge into the waterways of Tamil Nadu, India (Ramesh *et al.*, 1997)

Location	*Drainage* (km^2)	*Discharge* ($10^6\,m^3$)	*Industrial effluent mill. L* d^{-1}	*Domestic effluent mill. L* d^{-1}
Vellar-Coleroon	14	850	Nil	Negligible
Ennore Creek	70	NA*	0.45	3.4
Adyar River/Estuary	857	114	0.78	6.81

* Not available.

phosphorus during summer was the primary limiting factor. Nevertheless, phytoplankton primary productivity was sustained by release of nitrogen and phosphorus from the nutrient rich sediments. The nitrate concentration in surface waters of the Pichavaram mangroves ranged from 0.7 to 41.4 $\mu g\,l^{-1}$ during summer and monsoon respectively. During summer, nitrate is virtually removed from the water column mainly due to its utilization by the primary producers and the mangrove flora. Ammonia concentrations ranged from 133 $\mu g\,l^{-1}$ in monsoon to 597 $\mu g\,l^{-1}$ during post-monsoon with secondary peaks in summer, displaying a strong negative correlation [$n = 5$; -0.89; $r = 0.99$] with the nitrate and nitrite trends. Owens *et al.* (1986) report that concentration of ammonium tend to be higher during summer, as a result of excretion by the grazers, and a high bacterial decomposition of organic matter. The post-monsoon peaks in our study are attributable to active ammonification occurring during this period.

The temporal variations in the concentrations of phosphate and total dissolved phosphorus (TDP) in the Pichavaram, Ennore and Adyar mangroves, is shown in Figure 4. The level of phosphate in the Pichavaram mangroves ranged from 0.6 to 4.7 $\mu g\,l^{-1}$ recording the lowest concentration among the three mangroves studied. Typically, the concentrations were highest during monsoon (November) and lowest being during post-monsoon periods (March). Low concentrations are attributable to the fact that phosphate is perhaps not the dominant form of dissolved phosphorus in natural waters (Meybeck, 1982). Boto (1988) reported that phosphorus ions are rarely encountered as simple phosphate in solution, except under extremely alkaline conditions. Despite the presence of large amounts of phosphorus, its low solubility might limit phytoplankton growth in many coastal and marine ecosystems.

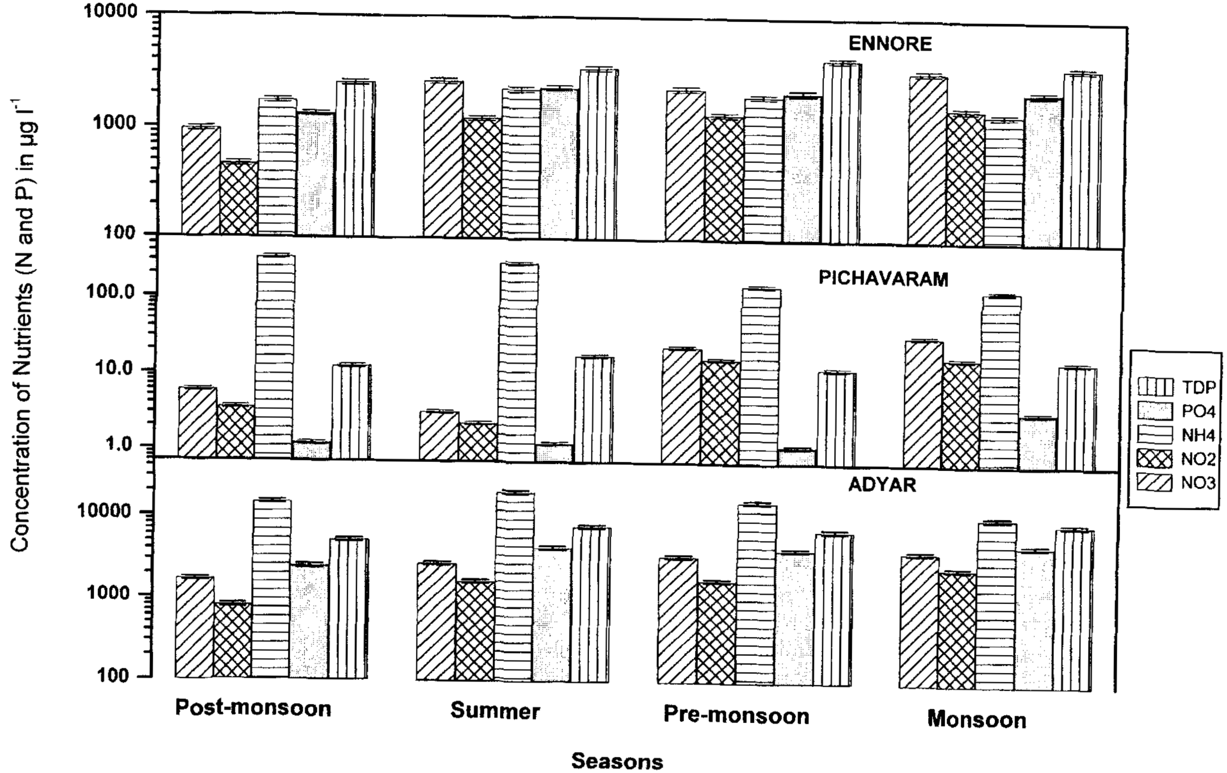

FIGURE 4 Seasonal variation of nutrients (nitrogen and phosphorus) in the mangrove ecosystems of Pichavaram, Ennore Creek and Adyar Estuary.

4.5. Nutrient Sources and Regeneration in Pichavaram Mangroves

Litter fall, perhaps forming a major fraction of net primary productivity in this mangrove ecosystem, is important in the maintenance of the detrital food web (Boto and Wellington, 1984; van Der Valk and Attiwill, 1984). The litter is composed of leaves, flowers, fruits, stipule and twigs. Of these, leaf litter contributes $\sim 50\%$ of the total litter. Flowers and fruits appear only in the reproductive phase of the plant. Twigs and other debris contribute 10 to 15% of the total litter fall (Swaminathan, 1993). An average of ~ 1.5 g dry wt $m^{-2} d^{-1}$ (0.18 to 3.2 g dry wt $m^{-2} d^{-1}$) which yields a total litter fall of 13.55×10^3 tons yr^{-1} for the entire mangrove area (241 ha) of Pichavaram. It has also been estimated that $\sim 46\%$ of nutrients are received from allochthonous sources while 54% is regenerated within the mangrove ecosystem (Purvaja, 1995), through litter decomposition. Thus the amount of nutrients received through recycling of mangrove detritus is much higher than from freshwater sources.

4.6. Nutrients in Polluted Mangrove Waters

As far as the Ennore and Adyar mangrove waters are concerned, both nitrogen and phosphorus were available in excess and phytoplankton primary productivity could not have been altered because of nutrient limitation (Fig. 3). The nitrate concentration was maximum at the Adyar Estuary mangrove waters (700 – 5200 $\mu g\, l^{-1}$) followed by Ennore mangroves (800 – 4400 $\mu g\, l^{-1}$). Ammonia concentrations were over 10 times higher at Ennore and > 100 times at Adyar in comparison to the Pichavaram mangroves (Fig. 4). The above results clearly suggest the magnitude of human influence on the nutrient concentration in the mangrove waters. Table II shows the amount of domestic and industrial effluent discharges in the study areas, to highlight the intensity of pollution stress on the mangrove waters.

The phosphorus loading was maximum at the Adyar Estuary mangroves (Fig. 4) and environmental control on seasonal variations were insignificant. In addition to receiving phosphorus from domestic effluents, the Adyar River is also used for a variety of laundry operations supplying an additional phosphorus load to the mangrove waters. According to Meybeck (1990), sewage (human wastes) makes a much greater contribution to phosphorus pollution (70%) than that from agricultural sources (animal wastes and fertilizer – 15% each). Even if phosphate detergents were eliminated, sewage would still be a greater source than agricultural runoff. This is in contrast to nitrogen pollution, which is dominated by animal wastes and fertilizers. Similar observations were made for the Ennore Creek mangrove waters, where the phosphate concentrations varied from 500 – 3300 $\mu g\, l^{-1}$. The use of phosphate fertilizer in modern agriculture coupled with fertilizer effluent discharges caused eutrophication of the surface waters in our study. These are perhaps the most visible results of human interference to the phosphorus cycle.

4.7. N : P Ratio in Mangrove Waters

Redfield *et al.* (1963) indicated that in natural waters, the concentration of available nitrogen over phosphorus are greatly reduced during the period of active growth. One or the other element may be almost absent while an excess of the other may remain in water. An average composition given for marine plankton in terms of the classic Redfield Ratio is $C_{106}N_{16}P_1$. This is an idealized ratio and the actual phytoplankton nutrient utilization ratios can vary from 5N : 1P to 16N : 1P (Ryther and Dunstan, 1971), depending upon the nutrients in water.

The N : P ratio in surface water for the three mangrove systems in our study, have been calculated from the average annual concentration and varies from 0.96N : 1P at Ennore Creek mangroves and 1.75N : 1P at Adyar Estuary to 15.2 N : 1P at the Pichavaram mangrove ecosystem. These results show that the behaviour of nutrients in the mangrove water column is highly complex and that a simple input from rivers constitutes only a minor part of the source. The Pichavaram mangrove waters however, represents an ideal example for an unpolluted ecosystem with N : P ratio close to the steady-state values (16N : 1P) postulated by Redfield *et al.* (1963). By analogy, the Ennore and Adyar mangroves show a distinct reduction in the N : P ratio due to anthropogenic disturbances. This situation has three principal causes. First, the ratio of N : P in the nutrient enriched polluted water is possibly lower than that of estuarine plankton, so that there is an excess of phosphorus left over in the mangrove waters upon consumption of all nitrogen. Secondly, due to denitrification (the bacterial reduction of dissolved nitrate to nitrogen and nitrite), nutrient nitrogen can be selectively lost from the mangrove waters. Finally, upon deposition in the sediments, nitrogen is regenerated much more slowly than phosphorus such that the N : P ratio of the regenerated nutrients is lower than that used by the plankton for primary productivity.

Berner and Berner (1987) also stated that pollution is a probable contributing factor to variations in the N : P ratio. It is evident that a direct relationship exists between nutrient availability and primary productivity in the mangrove waters. The N : P ratio, in addition to various other physico-chemical factors, govern the phytoplankton primary productivity rates in the surface waters of the mangrove ecosystem. Thus, nutrients from anthropogenic sources may assume greater significance at least for phytoplankton productivity in mangrove ecosystem, which are close to major cities and agricultural lands.

5. CONCLUSIONS

In this paper, the effect of (i) organic matter enrichment and (ii) direct nutrient additions on phytoplankton productivity in mangrove ecosystems are discussed. Nutrient enrichment primarily, the increases in dissolved inorganic nitrogen and phosphorus in mangrove sediments lead to excessive phytoplankton growth and high biological productivity. Our study has also highlighted the fact that biogeochemical cycles of nitrogen and phosphorus are not altered significantly in a natural, unpolluted ecosystem like the Pichavaram mangroves. Thus, it must be realized that the natural cyclic processes cannot be increased indefinitely and that there may be critical threshold, beyond which the system shifts to a negative mode of functioning.

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