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SHORT-TERM SEDIMENT ACCRETION DYNAMICS OF PICHAVARAM MANGROVE FOREST, TAMIL NADU, INDIA

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The influence of mangrove systems in advancing the process of sedimentation is very well studied over the years. However, understanding the actual mechanism of accretion at a specific point within a mangrove forest is difficult, due to the stochasticity of sediment distribution and deposition. Factors that influence the rate of sediment accretion within the mangrove forest such as plant litter accumulation and bioturbation were investigated in Pichavaram mangrove forest, India. The annual rate of vertical accretion was recorded as 1.5 ± 0.9 cm year^{-1} for the site at elevation 0.4 m, and 0.9 ± 0.04 and 0.9 ± 0.05 cm year^{-1} for the other two sites which are at -0.8 and -1.2 m respectively. Results show that the sites were accreting sediments but at varying rates, inter-site variability was low but the factors influencing the processes were different. Plant litter contributed significantly to the accretion, and organic matter estimates also supported this observation. A higher rate of organic matter accumulation was observed in one of the sites, which is not regularly inundated by tides. On the contrary, in sites which were regularly washed by tides, accretion was seen in both allochthonous and autochthonous inputs and the annual rate of vertical accretion was almost the same.

Keywords: Vertical accretion, stochasticity, marker horizon, sea level rise, litter production, sediment deposition

INTRODUCTION

Climate change is now widely accepted as a threat to coastal ecosystems as they struggle with more frequent and extreme storm events, flooding, irregular or increased precipitation, and rise in sea level (Sandifer & Scott 2021). Mangroves are a group of trees and shrubs that dominate the intertidal zone in the tropical and subtropical regions of the world. Mangroves and associated taxa occurring naturally on the coasts are resisting impacts and protecting the communities from large shifts in climate systems. However, depending on the local conditions, mangroves either submerge, adapt or retreat landwards. During sudden shifts of climate anomalies, the mangrove self-mitigation abilities will be impacted. Mangrove ecosystems serve as a focal point for understanding the processes that control elevation change in the intertidal setup (Webb et al. 2013). Some mangrove forests have been able to adjust to the sea level rise by facilitating sediment deposition and accumulation of peat (Ellison 2008). Therefore, monitoring mangrove forest accretion and/or elevation in multiple locations is necessary to develop an understanding of habitat stability in different environmental and sedimentary regimes.

Mangrove wetlands are highly vulnerable to submergence due to the rising sea level in most parts of the world but they also have strong ability to modify themselves and adapt to the changes and promote habitat persistence (Cheong et al. 2013). The rate of sea level rise has doubled from 1.4 mm year^{-1} throughout most of the 20th century to 3.6 mm year^{-1} in the period 2006–2015. In turn, the rate of change of elevation within the mangroves occurs slowly. Mangrove roots are excellent soil binders. The complex structure of pneumatophores and prop roots trap and build up sediment. In a mangrove system, around 80% of sediments are contributed by tides. Plant litter also contributes to the mangrove floor with rich organic matter. In conditions where tidal flushing is limited, leaf litter can accumulate and contribute to soil accretion. In the Florida basin/interior forests where the tidal flushing is low, leaf litter accretion rates range from 1.1 to 3.4 mm year^{-1} (McKee 2011). The complex root system of mangroves controls the velocity of sediment and enhances sediment retention. The density of pneumatophores is positively correlated with vertical accretion.

Accretionary processes within a mangrove forest are of utmost importance in contributing to overall soil elevation. The potential submergence of a mangrove wetland can be determined by measuring vertical accretion and comparing it with the relative rates of sea level rise (Cahoon et al. 1996). If the mangroves are not able to keep up with the sea level rise, then accretion deficit will occur. Mangroves directly or indirectly affect soil accretion by impacting the retention of inorganic sediment or accumulation of organic matter through various processes. Mangrove vegetation supplies a lot of organic sediment, derived from litterfall and decomposition. Leaf litter contributes to the majority of the total annual litter production followed by reproductive parts such as flowers, propagules and twigs (Castillo et al. 2017). Vertical accretion is, therefore, positively correlated with the accumulation of plant detritus (McKee et al. 2012).

Biotic factors have an important effect on the ecology and structure of mangrove forests. Crabs have a significant impact on energy flows within a mangrove ecosystem. Burrowing by crabs impacts the sediment chemistry, forest structure and productivity. Crabs carry organic and inorganic matter to their burrows, resulting in an increase in productivity and aeration of the mangrove forest. In the burrows, nitrogen is cycled by bacteria and sediments are oxygenated. When tides flood the burrows, ammonium and other nitrogen products are then flushed out (Robertson & Daniel 1989).

In this study, we made simultaneous measurements of vertical accretion at three sites, which are at varying elevations, in the Pichavaram mangrove forest in India to understand the accretionary process within the forest. Pneumatophore density and crab burrow hole density were counted in order to understand the effect of root growth and crab burrowing on accretion. Plant litter fall was also measured in order to understand the contribution of the plant to the accretionary process. The objective of the study was to identify how these factors affected the accretionary process at the three sites. The present research work was carried out for a duration of one year and simultaneous measurements of components contributing to vertical accretion were measured to gain understanding of the effect of each component on the accretionary process. This is the first reported study of vertical accretion in Indian mangroves. The findings of this research can provide valuable information for mangrove forest managers and policymakers to better understand the accretionary process and the factors that influence it. The methodology used in this study, including the simultaneous measurements of components contributing to vertical accretion, can serve as a model for future studies in other mangrove forests in India and beyond.

MATERIALS AND METHODS

Study area

The tropical mangrove system of Pichavaram was selected as the study area (Figure 1). Over the past few decades Pichavaram has suffered a 75% loss in forest cover due to reduction in freshwater supply, which led to formation of high saline clay zones in the sediment layers beneath the root zone (Singh & Rangarajan 2023, Gnanappazham & Selvam 2014). The Pichavaram mangrove forest is a dynamic tidal estuary at the confluence of Vellar and Coleroon Rivers along the eastern coast of Tamil Nadu, India. Pichavaram mangrove forest is located 225 km south of Chennai city and 5 km northeast of Chidambaram town in the Cuddalore district of Tamil Nadu. The forest spreads over an area of about 1470 ha in 2003 (Selvam 2003). Pichavaram has around 51 islets of various sizes due to intercrossing creeks and canals with depths of 0.5–1.5 m. Pichavaram is a shallow semidiurnal estuarine system with tidal amplitude varying from 0.15 to 1 m (Rangarajan et al. 2014). Tidal water requirements are met by the tidal flow through Vellar, Coleroon estuary and Chinnavaikal mouth (Kathiresan 2000). The high downstream flow during the monsoon fully opens the Chinnavaikal mouth, which remains partially opened for the rest of the year allowing very low tidal movement. The study area is also one of the most productive environments. It produces around 8 tonnes of organic plant detritus ha^{-1} year^{-1} (Mayalagu et al. 2009). Acreage of mangroves around the world is shrinking due to deforestation and conversion of forests into agricultural or aquaculture lands.

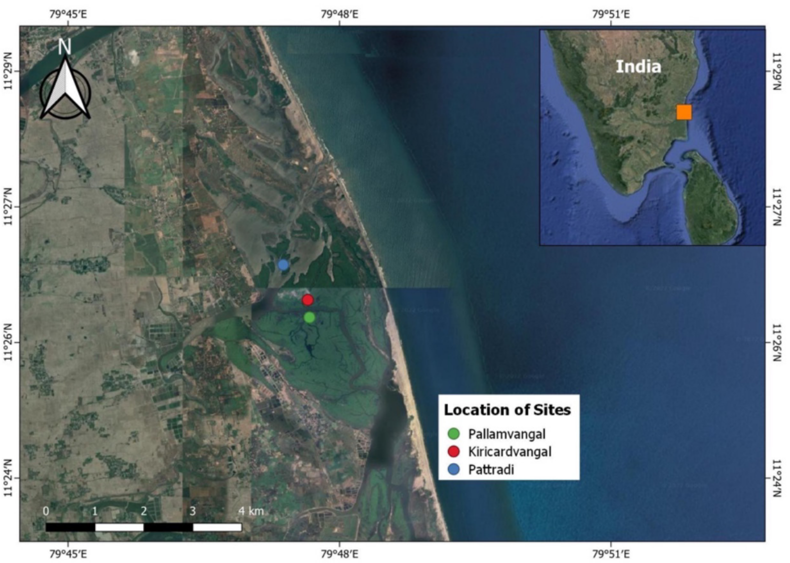

Figure 1 Location of Pichavaram mangrove forest, India and the sites for data collection

Methodology

Measurements were carried out monthly and bimonthly for a year from May 2021 to May 2022. The rate of vertical accretion, mangrove litter accumulation, crab burrow hole density and pneumatophore density were recorded. The research stations were determined using purposive sampling method based on the field assessment. Three sites at varying elevations were selected, namely, site 1 (Pattradi), site 2 (Pallamvangal) and site 3 (Kiricardvangal). Pattradi is at an elevation of 0.4 m asl while Pallamvangal and Kiricardvangal are at -0.8 and -1.2 m asl respectively. Site 1 experiences inundation only during extremely high-water events while sites 2 and 3 are regularly flooded. The correlation analysis was performed using SPSS to statistically understand the correlation between the variables and their significance.

Vertical accretion

The marker horizon method was adopted to determine the vertical sediment accretion in the study area. NPS protocol version 1.00 (January 2015) was adopted in establishing and sampling marker horizons. Marker horizons primarily measure the accumulation of sediment due to surface processes. Four marker horizon plots were established per site. A bimonthly sampling of marker horizons was done using cutting plugs technique (Cahoon et al. 2000). Feldspar was deployed on 0.5 m × 0.5 m plots, with replicate plots for each sampling location. A thick layer of feldspar (1–2 cm) was placed on the mangrove floor surface. A sharp 20 cm long serrated kitchen knife was used to cut plugs and a metric ruler was then used to measure the thickness of the layer. The soil plug was then gently pushed back into the ground. A total of 12 marker horizon plots were established at the three sites within the study area.

Plant litter production

Measurement of mangrove litter production used the litter trap technique. The trap consisted of a nylon mesh of size 1 m^2. It was placed at a height of around 1 m above ground to avoid tidal interferences. Litter traps were installed in the Rhizophoraceae and *Avicennia* zones to understand the variation between the two. Litterfall was collected and weighed once every two months. The litterfall was first separated into three litter components, namely, leaves, flowers and branches/twigs. The litter sample was then air dried for 48 hours before weighing.

Crab burrow hole and pneumatophore densities

Sesarmid and *Uca* crab burrow holes were counted in four quadrants of size 1 m × 1 m each for all three sites. Within each quadrate, the number of pencil roots was counted (Dahdouh-

Guebas et al. 2007). Measurements were taken bimonthly for a year (May 2021–May 2022).

RESULTS AND DISCUSSION

Vertical accretion

Bimonthly measurements of sediment accretion showed that accretion values of the three sites in Pichavaram mangrove forest varied significantly throughout the year and there was a net positive accumulation of sediments (Figure 2). The annual rate of vertical accretion was 1.5 ± 0.9 cm year^{-1} for site 1 and 0.9 ± 0.04 and 0.9 ± 0.05 cm year^{-1} for sites 2 and 3 respectively. The annual vertical accretion did not vary much between the three sites although it was clear that erosion or lesser accumulation was seen at the sites of lower elevations, which were regularly washed by tides. All feldspar markers were buried right after establishment (March 2021) within a period of one month. The rate of vertical accretion of site 1, Pattradi, exceeded those recorded for the other two sites. Two different accretionary environments were identified between the three sites based on the soil properties, namely, rate of plant detritus accumulation and reach of tidal inundation.

All four marker horizons in the tidally-restricted site 1, Pattradi, were recovered neatly and showed no signs of erosion after one year. The average percentage of organic matter in the top 5 cm of soil was around 7.57% and was primarily composed of plant detritus and root matter (results not shown). Being irregularly flooded, Pattradi receives much less sediment input and had the lowest mineral accumulation and higher percentage of organic matter compared with the other two sites. With less tidal movement, a visibly thick dense layer of plant detritus accumulated on the mangrove floor. Visual examination of the soil cores revealed that plant litter contributed significantly to the accretion above the feldspar layer. On the other hand, sites Pallamvangal and Kiricardvangal were regularly washed by tides, and accretion was seen in both allochthonous and autochthonous inputs. The soil organic contents were 1.62 and 1.74% for sites 2 and 3 respectively. Pattradi has a visible algal turf, which supports binding of sediments (Krauss et al. 2014). Growth of *Rhizophora* spp. was higher at sites rich in decomposed organic deposits and this concurs with findings by Nur-Hafiza et al. (2023).

As the organic matter content was low at Pallamvangal and Kiricardvangal because of the continuous washing of plant detritus by tidal action, accretion was also lesser for these sites. The hydroperiod at Pattradi is primarily controlled by rainfall rather than tidal exchange, although the basin flooded during exceptionally high-water events. Thus plant detritus affect the vertical accretion at Pattradi more than the other two sites, Pallamvangal and Kiricardvangal.

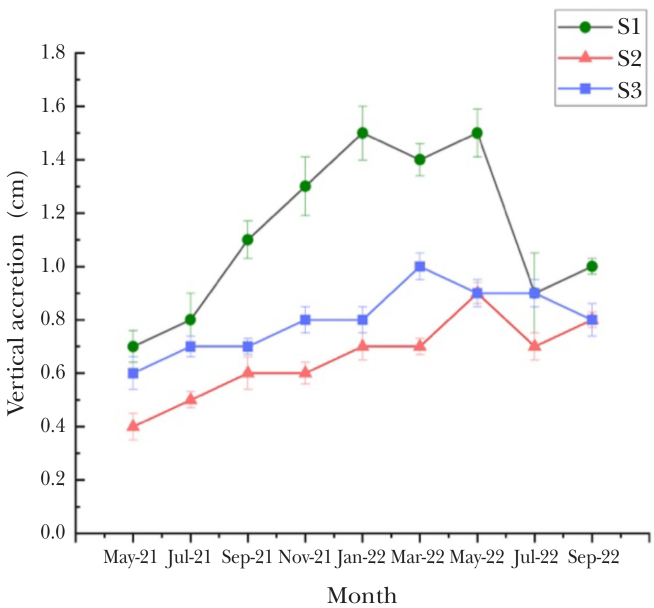

Figure 2 Vertical accretion at the three study sites in Pichavaram mangrove forest; S = site

The mean vertical accretion for Pattradi varied from 0.7 ± 0.06 to 1.5 ± 0.09 cm. The effects of increased rain, leaf shedding and crab growth season on sediment accumulation were evident. Monsoon and post-monsoon months i.e. September, November and January 2021 had greater rates of sediment accretion at all three sites. The accretion in March 2022 was lesser than in January 2022, suggesting a lower rate of accumulation of sediments or erosion, shrinkage, and/or compression. Seasonal rains in Tamil Nadu end in February. However, in an unusual turn of events low pressure brewing in the Bay of Bengal brought heavy rainfall in the first week of March 2022. Cuddalore and the nearby district Nagapattinam experienced very heavy rainfall in that month. The sudden reduction in accretion can be an effect of unprecedented rainfall events. Mean vertical accretion in Pallamvangal varied from 0.4 ± 0.05 to 0.9 ± 0.04 cm. The variation in sediment accretion for this site was linear with similar readings for July and September 2021 as well as January and March 2022. The effect of monsoon was not evident at this site. Mean vertical accretion for site 3, Kiricardvangal, varied from 0.6 ± 0.06 to 0.9 ± 0.05 cm. Site 3 is similar to site 2 in many ways. The annual rate of vertical accretion was almost the same after the sharp increase in accretion in March 2022 and further decrease in May (Figure 2). The effect of unprecedented rainfall in March 2022 had a contradictory effect on both sites 2 and 3. As these sites are on either side of the canal as shown in Figure 1, Kiricardvangal experienced an increase in accretion rate and Pallamvangal, a reduction. The rainfall event in March 2022 in Pattradi must have caused washing of plant litter leading to sudden decrease in the rate of accretion. It can be noted that small but unprecedented changes in weather events impact the accretionary process in the mangrove forest.

Plant litter production

From the bimonthly drying and weighing of plant litter collected on litter traps installed in the *Rhizophora* and *Avicennia* zones, we observed that the *Rhizophora* spp. at the three sites contributed 50% more to plant litter than *Avicennia* spp. (Figure 3). The annual litter production values for Pattradi were 400.98 and 608.93 g m^{-2} for the *Avicennia* and *Rhizophora* zones respectively. September (40.54 g m^{-2}) and March (74.33 g m^{-2}) had the lowest and highest values of plant litter collected. Of the three litter components viz., leaves, flowers and twigs/branches, leaves contributed the most to litter production (Table 1).

Site 3 has a denser canopy than sites 1 and 2. Therefore, the litter production was maximum for site 3, Kiricardvangal, in both *Avicennia* and *Rhizophora* zones (Figure 3). Litterfall was low at higher elevation i.e. site 1, but higher at lower elevations (sites 2 and 3). Though more litter would have been produced in sites 2 and 3 because of their denser canopies, the higher tidal action had swept away some of the litter. As a result, site 1 exhibited higher value than the other two sites. We observed that site 1 had a clear layer of plant detritus, which was absent at the other two sites. Litter production of *Avicennia* species was the lowest in July and September and maximum in March for all three sites. For the *Avicennia* zone, flowers were recorded for a duration of five months, starting from September and ending in January (Table 1). The flowering season peaks in the middle of September and lasts till the end of October. In the case of the *Rhizophora* spp., the flowers last longer and were recorded year-round except in March and April, peaking in September. Table 1 shows the details of plant litter components recorded from May 2021 to May 2022.

Crab burrow hole and pneumatophore densities

The crab population peaks during monsoon and post-monsoon months, i.e. September, November and January in Pichavaram and this is supported by the number of crab burrow holes recorded in this study. The increased number of burrow holes may not be directly related to the crab population but crab burrow density has a positive effect on the sediment accretionary process. The number of crab burrow holes observed in the *Avicennia* zone for the three sites is represented in Figure 4. Crabs descend from burrows, which are above the high tide mark, and take back leaves to the burrows in order to leach out tannins before consumption. A single crab tends to make multiple burrows to store the leaves and later consume them. This process of bioturbation affects sediment accretion positively. Among the three sites, Pattradi recorded the maximum number of crab burrow holes. The elevation of

Table 1 Plant litter components collected bimonthly from May 2021 to May 2022

Site	Zone	Litter component (g m^{-2})	May 2021	July 2021	September 2021	November 2021	January 2022	March 2022	May 2022
1	*Avicennia*	Leaves	55.63	32.57	31.88	42.47	35.62	68.59	67.57
		Flowers	-	-	3.56	1.35	-	-	-
		Twigs/Branches	11.72	13.79	5.10	9.66	13.94	5.74	1.78
	Rhizophora	Leaves	79.29	60.38	67.29	59.28	61.28	89.28	83.22
		Flowers	-	2.46	9.29	7.24	7.30	1.49	3.58
		Twigs/Branches	12.35	18.46	9.24	10.18	15.35	8.40	3.57
2	*Avicennia*	Leaves	68.20	48.28	44.30	62.30	52.42	78.29	70.28
		Flowers	-	-	5.93	5.25	2.46	-	-
		Twigs/Branches	18.38	13.79	7.20	10.58	18.40	9.38	15.48
	Rhizophora	Leaves	95.49	74.29	93.28	83.53	93.39	110.28	97.19
		Flowers	3.56	5.40	17.28	13.26	7.29	5.40	5.40
		Twigs/Branches	16.38	13.79	15.49	12.48	15.25	14.29	18.40
3	*Avicennia*	Leaves	92.28	54.29	57.29	79.27	90.27	115.17	95.29
		Flowers	-		6.28	4.25	2.44	-	-
		Twigs/Branches	18.38	10.46	8.25	12.49	17.28	10.48	17.37
	Rhizophora	Leaves	101.39	87.19	89.19	95.19	97.08	148.86	107.18
		Flowers	6.29	7.28	18.38	17.28	10.28	7.19	4.28
		Twigs/Branches	14.38	18.28	17.28	16.28	14.29	13.17	13.18

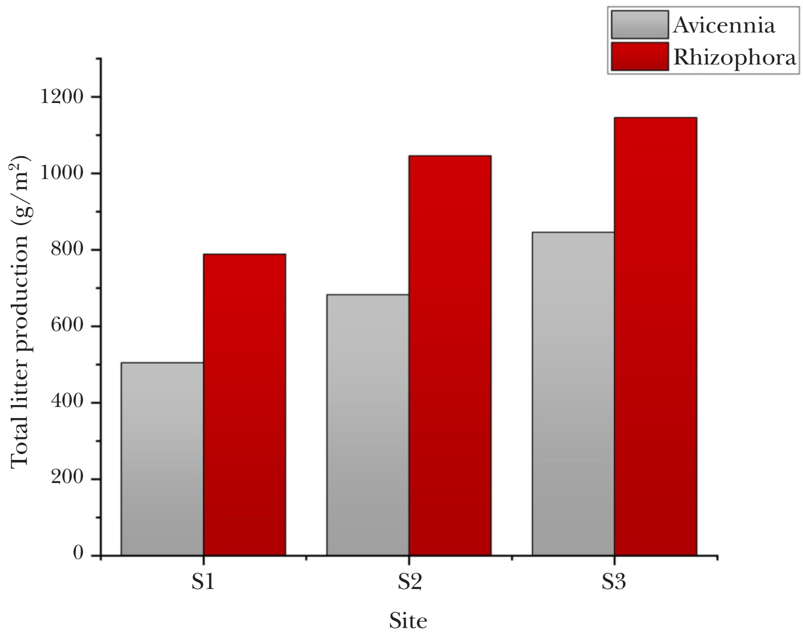

Figure 3 Annual litter production in *Avicennia* and *Rhizophora* zones

the basin and the presence of burrows above the high tide mark make it the most favourable site among the three.

Canopy cover positively affects crab hole densities because shade decreases the temperature and rate of evaporation (Feliciano et al. 2017, Karniati et al. 2021). In this study, the density of *Uca* species was affected more by low-density canopy cover. Crab population in this study was highest during the monsoon and post-monsoon

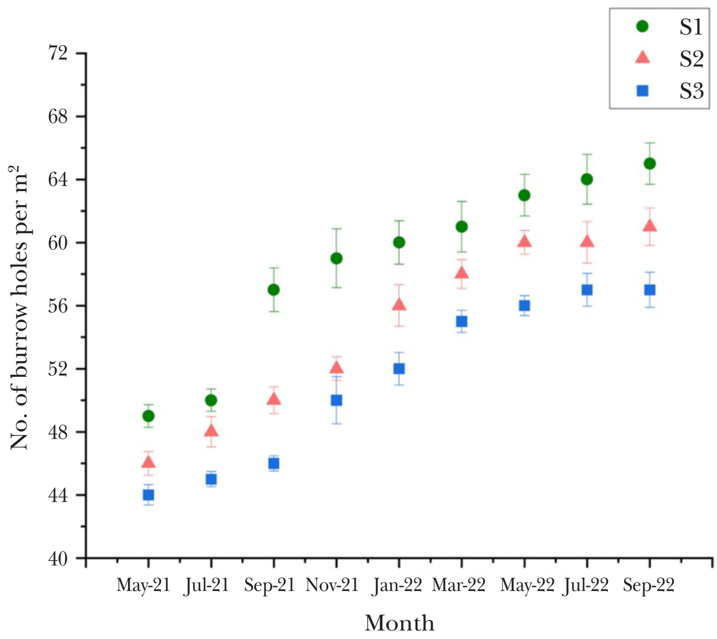

Figure 4 Variation in crab burrow hole density over the months

phases. The reason is the extensive availability of organic carbon during these seasons. Even though the leaf litter production of site 1 was lower than in sites 2 and 3, the crab burrow hole density was highest because of its elevation. Site 1 has an irregular but dense canopy with flooding only during high water events.

Pneumatophores are known to stabilise sediments. Varying root distribution in mangrove forests results in varying sediment charateristics (Fiala et al. 2017). Pneumatophore densities were counted in the natural *Avicennia marina*-dominated zones of the Pichavaram mangrove forest. Pneumatophore density increases with a longer period of inundation (Dahdouh-Guebas 2007), as observed in this study. Site 3, which has a longer period of inundation than the other two sites, recorded the highest number of individual pneumatophores. Regular inundation of the site and the presence of juvenile plants can be a reason for this higher pneumatophore density. Pneumatophore densities of Pichavaram mangrove forest ranged from 151 to 237 individual pneumatophores m^{-2} (Figure 5). Pattradi had a relatively sparse presence of pneumatophores in comparison to the other two sites. In general, the more the pneumatophores, the more sediment retention. Even though sites 2 and 3 had dense pneumatophores, accretion was lower than that of site 1. This points us to the effect of tidal washing on the low-lying mangrove islands. Roots definitely promote accretion but, in this case, strong tides were carrying the sediments along. Both sites 2 and 3 are at lower elevations and sediment retention was poor.

Relationship between the variables

Vertical accretion, litter production, pneumatophore density and crab burrow hole density are positively and significantly correlated between all three sites. Average values of the annual litter production for the three sites were 541.2 g m^{-2} in the *Avicennia* zone and 774.7 g m^{-2} in the *Rhizophora* zone (Figure 3). Quantity and quality of plant detritus determine the functioning of a forest ecosystem. Pichavaram is a highly productive environment supporting a wide variety of intertidal flora and fauna. The major cause of movement and/or disappearance of plant detritus from sites 2 and 3 was tidal washing. Many studies have proved that older plants produce less litter production. It was also noticed that the denser canopy and the younger trees of site 3 were producing more plant detritus than sites 1 and 2 which had older and sparse canopy. Litter production and decomposition processes have a significant role in healthy functioning of tropical ecosystems.

Mangrove roots lower the water velocity and enhance sediment trapping. Vertical accretion of sediments had a positive correlation with the

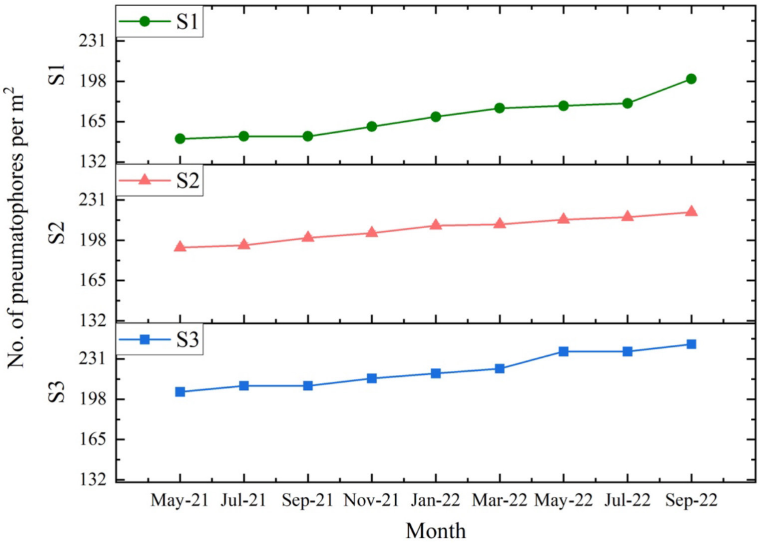

Figure 5 Variation in pneumatophore density over the months; S = site

abundance of pneumatophores. In all three sites, the correlation between the accretion and abundance of pneumatophores is significant (Figure 2 and 5). *Avicennia marina* is able to adapt to the changes in microtopography as a response to sea-level changes (Dahdouh-Guebas 2007). Crab burrow holes cover a large area of Pichavaram mangrove forest and the influence of bioturbation by crabs on sediment accumulation cannot be neglected. The patterns of crab burrow distribution and the diameters of the burrow holes were different between the three sites. Crab population might be the main reason for the differences in sediment accretion between the three sites. The sizes of the crab holes were smaller in sites 2 and 3 compared with in site 1. Juvenile crab burrows were found in low elevation areas because the tidal action would favour them for release and dispersal of larvae. Breeding occurs in the lower elevation region and adult crabs move to higher regions. Breeding season and migration of crabs can affect the overall process of bioturbation, which needs to be studied in detail.

Vertical accretion and sea level rise

Rising sea level has a very direct and prompt effect on coastal ecosystems. Stresses associated with rising sea levels and increased frequency of high-water events, storms and fluctuating rainfall pose threats to intertidal ecosystems like mangroves. Khan et al. (2016) predicted the ranges of local sea level rise for all scenarios suggested in the IPCC Fourth Assessment Report (IPCC 2000) for the Pichavaram mangrove forest. They reported that the sea level rise will range from 1.03 to 5.95 cm for the year 2025 and from 1.72 to 16 cm for the year 2050. The present annual accretion rate for Pichavaram is 1.1 ± 0.33 cm $year^{-1}$ (2021–2022), which is higher than the lowest value of predicted sea level rise for the year 2025. If this rate of accretion is maintained in the forest zone, the areas at higher elevations could possibly withstand the predicted sea level rise with minimum adaptation strategies adopted. However, the low-lying areas will be in serious threat of submergence even at the minimum predicted rise and the authorities need a plan of action in place. Pichavaram mangroves are not uniformly accreting enough to survive a rapid sea level rise. This is the case when there is no freshwater input in the forest. Pichavaram mangroves respond to sea level rise by positively accreting and rising its mangrove floor surface only in the northern part. With an increase in the intensity of climate change events in the future Pichavaram mangroves will not be able to accrete enough sediments to maintain its floor surface higher than the sea level.

CONCLUSION

Measurements of sediment accretion were recorded over a one-year period in the Pichavaram mangrove forest, and the results demonstrated a net positive accumulation of sediments at the three study sites. *Rhizophora* spp. contributed

1.5 times that of the plant litter production in the forest than the *Avicennia* spp. Annual litter production values for the three study sites varied, with the highest values observed in the *Rhizophora* zone at site 1 and the densest canopy site, site 3. The *Avicennia* zone had higher numbers of crabs and crab burrow holes compared with the *Rhizophora* zone. Site 1 had the highest number of crab burrow holes due to its favourable elevation and the presence of burrows above the high tide mark. The density of *Uca* species was affected by the canopy cover and the distribution of crabs within the mangrove sites changed with the canopy cover. The density of pneumatophores in the mangrove forest was positively correlated with the period of inundation, and the site with the longest period of inundation had the highest number of individual pneumatophores. The present annual accretion rate in Pichavaram is 1.1 ± 0.33 cm year^{-1}, which is higher than the lowest value of predicted sea level rise for the year 2025. However, the low-lying areas of the Pichavaram mangroves are in serious threat of submergence even at the minimum predicted rise and need a plan of action in place. Pichavaram mangroves are not uniformly accreting enough to survive a rapid sea level rise and with the higher intensity of climate change events in the future, Pichavaram mangroves will not be able to accrete enough sediments to maintain its floor surface higher than the sea level. Therefore, there is an urgent need to plan future mitigation strategies for Pichavaram mangroves. This study can help authorities to implement similar studies in other mangrove forests in India, to identify the factors affecting vertical accretion, and to develop management strategies to maintain or enhance accretion rates.

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