Available online at: www.mbai.org.in
doi:10.6024/jmbai.2022.64.2.2220-01

Sediment blue carbon stock of *Avicennia officinalis* in Vembanad Lake ecosystem, Kerala, India

G. S. Arathy, D. Prema*, Shelton Padua, V. Kripa, R. Jeyabaskaran, Eldho Varghese, R. Lavanya, P. Vysakhan, M. P. Syamala and Seban John
ICAR-Central Marine Fisheries Research Institute, Kochi- 682 018, Kerala, India.
*Correspondence e-mail: premadicar@gmail.com

Received: 30 July 2020 Revised: 30 June 2022
Accepted: 15 July 2022 Published: 03 Oct 2022

Original Article

Abstract

Stock assessment of the blue carbon pool of selected patches of mangrove sediment in the Vembanad Lake was done using the standard protocols on a per ha basis and multiplied with the estimated area to derive the blue carbon stock of the particular fragmented mangrove stands of the species *Avicennia officinalis* (Indian Mangrove), twice (in the post and pre-monsoon) during October 2017-March 2018. The treatments included 'aged', 'recent', 'healthy' and 'degraded' mangroves of the selected species and 'control' without mangroves. The overall mean carbon stock in the *A. officinalis* sediments in selected locations of the Vembanad Lake area was 136.09 Mg C/ha (Mg=mega gram=1 tonne). This value is far low compared to the mean global soil organic carbon stock in the mangrove ecosystem (386 Mg C/ha). This finding suggests ample opportunity for more carbon sequestration in the selected mangrove ecosystems in Vembanad Lake, toward climate change mitigation measures. The treatments differed significantly in the cumulative stock of blue carbon and layer-wise blue carbon density in sediment ($p<0.05$), the highest seen in 'healthy' mangroves in both seasons. The overall range of layer-wise blue carbon density in sediment was found to be 0.003 to 0.56 Mg/m^3. Spatial maps prepared for layer-wise blue carbon density in the sediment revealed its depth-wise increase. Layer wise blue carbon stock in sediment had a significant correlation with total organic carbon and organic matter ($p<0.01$) and with the C/N ratio of the sediment ($p < 0.05$). Based on the results, this study suggests total organic carbon and the C/N ratio of sediment as possible predictive indicators of sediment blue carbon.

Keywords: *Mangrove sediment, blue carbon, dry bulk density, climate change, GIS, Vembanad Lake*

Introduction

The carbon stored by coastal and oceanic ecosystems is known by the term blue carbon. The coastal blue carbon includes the stored carbon in mangroves, salt tidal marshes and seagrass meadows within the soil as well as in the living biomass above ground and below ground (Mcleod *et al*., 2011). Coastal ecosystems, of which a major part is mangroves, play a key role in the national wealth of maritime countries, providing ecosystem goods and services to the coastal community. The coastal ecosystems sequester more carbon in sediment than terrestrial ecosystems and the carbon remains trapped for a very long time adding up the carbon stocks to huge amounts if allowed to remain undisturbed. This blue carbon can be freed into the atmosphere as CO_2 when these ecosystems are converted or degraded (Pendleton *et al*., 2012). Hence these ecosystems need to be conserved to give a boost to the climate change mitigation efforts.

Mangroves capture and stock up large amounts of carbon from the atmosphere and the sea (Yee, 2010). The mangroves fix carbon, depending upon the light intensity, species composition, nutrient and water availability, salinity, tides, waves, temperature and climate. The mangroves help in storing carbon to reduce the impact of climate change (Alongi, 2014). In India, Patil *et al.* (2012) reviewed the carbon sequestration potential of mangroves. Mangroves act as a significant sink for CO_2 and so have a considerable role in sequestering carbon and reducing greenhouse gases.

The carbon sequestration potential of various ecosystems is of concern as the atmospheric CO_2 concentration goes on increasing steadily. But in India, studies on carbon sequestration potential were mainly on agriculture and forest ecosystems, barring a few from seaweed (Kaladharan *et al.*, 2009), seagrass (Kaladharan *et al.*, 2020, 2021) and mangrove ecosystems (Kathiresan *et al.*, 2021).

The total area of mangroves in India is 4921 km^2 (FSI, 2017). The area of mangroves in Kerala comes to 2502 ha and the district of Ernakulam is the second in Kerala to have patches of mangroves (Vidyasagaran and Madhusoodanan, 2014). Mangrove patches in the Vembanad Lake, which is one of the most dynamic, life-supporting coastal wetlands of Kerala, facilitate the production of detritus, organic matter, recycling nutrients and improvement of coastal production (Mogalekar *et al.*, 2015). The present study scrutinized sediment blue carbon stocks of Vembanad Lake, for mangrove patches of *Avicennia officinalis* in selected locations in Ernakulam District.

A. officinalis is one of the common species which could establish in different mangrove formations in the state of Kerala (Vidyasagaran and Madhusoodanan, 2014). The dominance of *Avicennia* spp. is high (70%) and is found in the proximal zones of Vembanad Lake (Mogalekar *et al.*, 2015). Among the different mangroves, *A. officinalis* represents 41% of the total Important Value Index (the totality of the relative frequency, relative density and relative dominance) in Kerala (George *et al.*, 2018).

As per IPCC (2007), by the year 2050, global CO_2 emissions must come down by 85% from the levels seen in 2000 to restrict the global mean temperature increase to 2°C through mitigation measures, *ie.*, reducing the anthropogenic CO_2 sources while supporting CO_2 intake and storage through the conservation of natural ecosystems with high C sequestration rates and capacity. Mangroves store more carbon in the sediment in comparison to the above-ground parts which remain stored in several meters of depth for centuries or more if undisturbed (CCC, 2017). According to Avelar *et al.* (2017), the study of carbon stock in soil /sediment is for a better understanding of the quantity and vulnerability of carbon stocks in these systems and the results can reveal potential implications for the management of human activities in coastal environments.

Scientific evaluation of the carbon sequestration capacity of mangrove ecosystems and their potential role in climate mitigation in comparison to terrestrial systems has been done on the west coast of India in selected estuaries (Vinod *et al.*, 2018, 2020; Varghese *et al.*, 2021), but not in the Vembanad Lake.

Hence the present investigation was taken up to estimate and map the blue carbon stocks in the sediments of Indian mangroves in selected locations of Vembanad Lake Ecosystem, Ernakulam, Kerala. The study also evaluated the impact of age and health of Indian mangroves, on blue carbon stocks in sediment.

Material and methods

Location

Samples were collected from selected locations of Vallarpadam, Kundanoor, Kumbalam, Mangalavanam, Thevara, Malipuram and Puthuvype areas of Vembanad Lake. Altogether 25 stations were fixed for the study as depicted in the location maps (Fig. 1),making use of Google Earth imageries and delineating the micro-level boundaries. The sampling was done in two seasons *viz.* post-monsoon (October – November 2017) and pre-monsoon (February- March 2018). The observed stand of *A. officinalis* (Indian mangrove) was classified into four treatments *viz.* aged, recent, healthy and degraded. Control stations were taken from the same areas selected for the study but without mangrove stands. The sites having *A. officinalis* with age >15 years were considered as aged (T2) and <5 years as recent (T3), the age being found out through local enquiry. The treatments 'healthy' (T4) and 'degraded' (T5) were classified based on their canopy cover, initially while fixing sampling locations through the visual interpretation of Google Earth imageries and further verifying through *in situ* visual observation. The *A. officinalis* stands, having dense canopy cover, were considered healthy whereas the *A. officinalis* stands having sparse canopy cover, as a result of anthropogenic activities were considered degraded. The general stand of *A. officinalis* in the study is taken into account as different treatments as shown in Fig. 2.

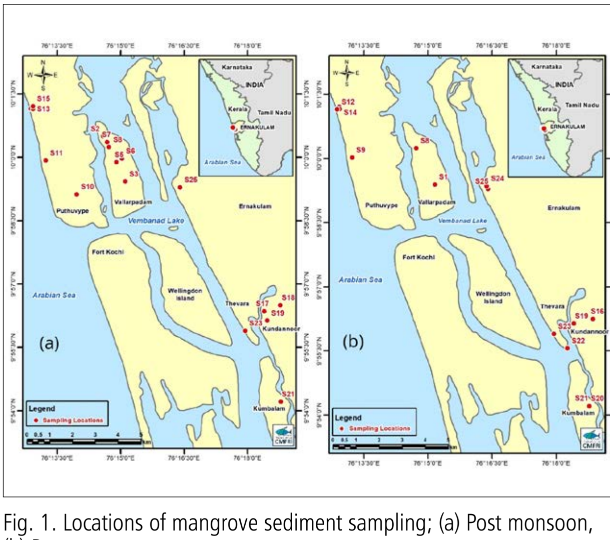

Fig. 1. Locations of mangrove sediment sampling; (a) Post monsoon, (b) Pre monsoon

Fig. 2. Typical sampled areas with *A. officinalis* cover; (a) Aged, (b) Healthy, (c) Degraded, (d) Recent

Sediment sample collection

The sediment samples were collected using custom-made soil core samplers of 1.0 m in height and 5.0 cm in diameter, closed with a pressing lid for both open ends. The core pipes were inserted into the sediment to a depth of 1m after removing the lids. After driving the core pipe into the sediment, the upper end is closed with the lid, then the core is pulled out carefully and the lower end of the core is also closed with the lid. In each station, two cores were taken, one exclusively for analyzing sediment bulk density and the other for analysis of all other sediment characteristics.

Sediment sample processing

In the laboratory, the cores were cut into 10 cm long sections, up to a depth of 50 cm, and 25 cm long sections after 50 cm (0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-75 cm and 75-100 cm) as per availability of intact sediment in the cores and were transferred into labelled trays for air drying. For the determination of pH and Eh, the wet samples were used. The samples kept for air drying were used for measuring salinity, total organic carbon, total organic matter, total nitrogen, total carbon, C/N ratio and sediment texture. For the analysis of bulk density, the samples were cut into 10 cm long sections, up to a depth of 50 cm, and 25 cm long sections after 50 cm (0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-75 cm and 75-100 cm) as per availability of intact sediment in the cores and transferred into labelled previously weighed glass containers. Then the samples were kept for oven drying at 60˚C, till attaining constant dry weight. The samples having core compression and also core sections having water in place of sediment were not taken for laboratory analysis. Wherever intact sediment samples were available in the core, blue carbon stocks up to the maximum available depth were measured. Core samples up to 30 cm depth with 10 cm intervals were uniformly available in all the cores and were subjected to all laboratory analytical procedures and these results were used for data analysis and interpretation. The sediment blue carbon is expressed in Mg (megagram *ie* 1 tonne).

Sediment analysis

For the estimation of sediment blue carbon and other sediment parameters, standard protocols were adopted for sediment collection, processing and laboratory analyses. Laboratory analyses were carried out with precision and quality check following the standard methods (Table 1).

Statistical analysis

Data obtained based on laboratory estimations were statistically analyzed using R 3.5.1. ANOVA was carried out to find out significant differences among the treatments and the depths.

Table 1. Sediment analytical methods

Sediment parameters	Method	Reference
pH	pH meter	Boyd and Tucker (1992)
Oxidation Reduction Potential	ORP tester	Hesse (1971)
Total organic carbon	Walkley and Black's titration method	Jackson (1958)
Total organic matter	1.724 × % organic carbon	Jackson (1958)
Salinity	Mohr and Knudsen titration method	Jackson (1958)
Sediment texture	International pipette method	FAO (1976)
Dry bulk density	Mass of dry soil (g) / Original volume of sampled sediment (cm^3)	Howard *et al.* (2014).
Total carbon and Total Nitrogen	CHNS analyzer	Howard *et al.* (2014)
C/N ratio	%TOC / % total nitrogen	Howard *et al.* (2014)
Sediment blue carbon stock in each core	Total core carbon (Mg C/ha) = Summed core carbon (g/cm^3) *(1 Mg/1,000,000 g) * (100,000,000 cm^2/1 ha)	Howard *et al.* (2014)

Wherever ANOVA results showed significant differences, post hoc analysis was carried out to know which treatments were significantly different from others. Correlation analysis was done to find out the inter-relationship of the parameters used for the study. Linear regression models developed based on the depth-wise change of the blue carbon content were used to extrapolate the blue carbon stock estimates up to 1 m depth wherever the sampling up to 1 m depth was hindered due to core compression.

Mapping

The high-resolution imageries available in the public domain were used to identify the location and to derive the extent of selected mangrove patches in the study area. These operations were done in a GIS environment. Sediment profiles of blue carbon stock up to 1 m depth were used to develop the 3D map of blue carbon stock. Preparation of 2D and 3D maps of sediment blue carbon density was done using Arc GIS 10.0 and Voxler 4.

Results

Primary factors considered for assessment

Sediment blue carbon stock: Cumulative stock of blue carbon in the sediment of *A. officinalis* in all sampling locations (Fig. 3) ranged from 6.00 to 39.00 Mg/ha, 6.43 to 83.52 Mg/ha and 17.10 to 139.96 Mg/ha at 0-10 cm, 0-20 cm and 0-30 m of depth respectively in post monsoon. In pre-monsoon, the variation of blue carbon stock was from 2.00 to 35.00 Mg/ha, 9.88 to 55.38 Mg/ha and 17.10 to 84.58 Mg/ha at 0-10 cm, 0-20 cm and 0-30 cm of depth respectively. Layer wise blue carbon density in sediment core sections of all sampling locations ranged from 0.06 to 0.39 Mg/m^3, 0.003 to 0.49 Mg/m^3 and 0.02 to 0.56 Mg/m^3 at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively in post-monsoon and from 0.02 to 0.35 Mg/m^3, 0.02 to 0.33 Mg/m^3 and 0.02 to 0.34 Mg/m^3 at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively. The values of layer-wise blue carbon density in sediment in both seasons, at depths of 0-10 cm, 10-20 cm and 20-30 cm are depicted in Fig. 4. In the top layer (0-10 cm), there was a significant difference among treatments.

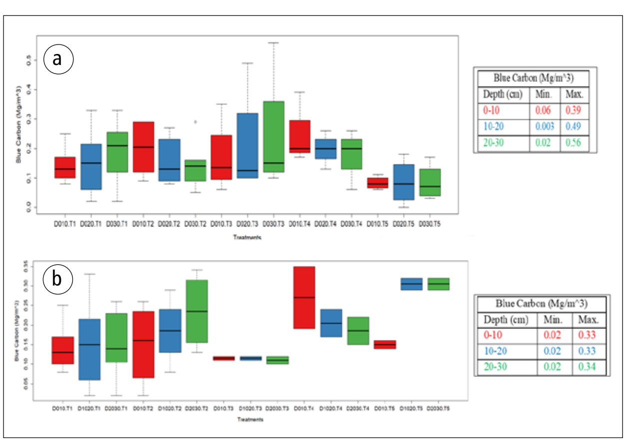

Fig. 3. Layer-wise stock of blue carbon in the sediment of *A. officinalis* at selected locations of Vembanad Lake; (a) Post monsoon, (b) Pre monsoon

Mapping: The maps showing layer-wise blue carbon stock in the sediment of *A. officinalis* at selected locations of Vembanad Lake at 0-10 cm, 10-20 cm and 20-30 cm in post and pre-monsoon are given in Fig. 5 and 6. The three-dimensional depiction of the profile of the sediment blue carbon stock in the mangrove patches of selected locations of Vembanad Lake is shown in Fig. 7, delineating the difference in the blue carbon accrue in 1m sediment profile, as per the selected treatments *viz.* aged mangrove stand, Recent mangrove stand, Healthy mangrove stand and the Degraded mangrove stand. The area of the studied patches varied from 0.01 ha to 59.86 ha with a mean area of 3.2 ha and the total extent was 80.51 ha. The sediment blue carbon storage varied from 21.16 Mg C/ha to 325.26 Mg C/ha with an average value of 136.09 Mg C/ha. Depending on the extent of the mangrove patches and the carbon storage density, the blue carbon stock varied from 0.21 Mg C to 18704.04 Mg C for different patches and the total blue carbon stock in the studied area

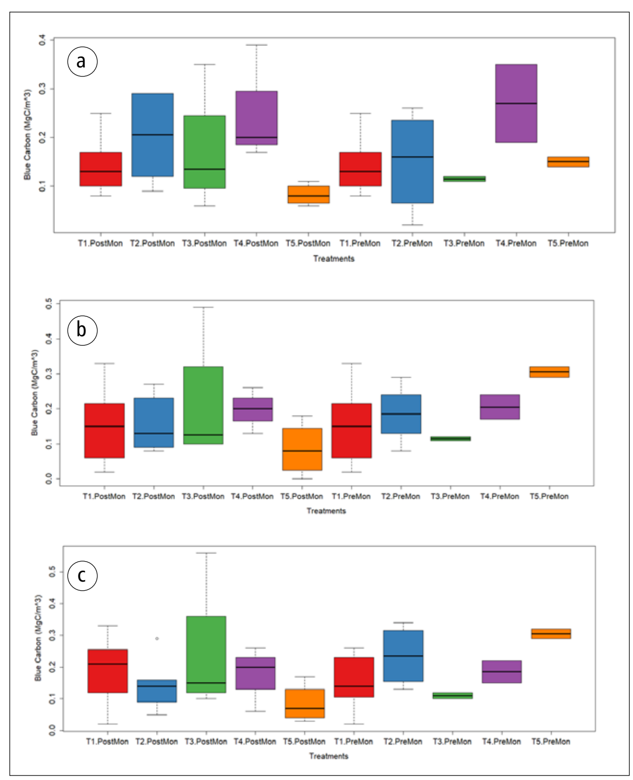

Fig. 4. Pooled seasonal depiction of layer-wise blue carbon in the sediment of *A. officinalis* at selected locations of Vembanad Lake; (a) 0-10 cm depth, (b) 10-20 cm depth, (c) 20-30 cm depth

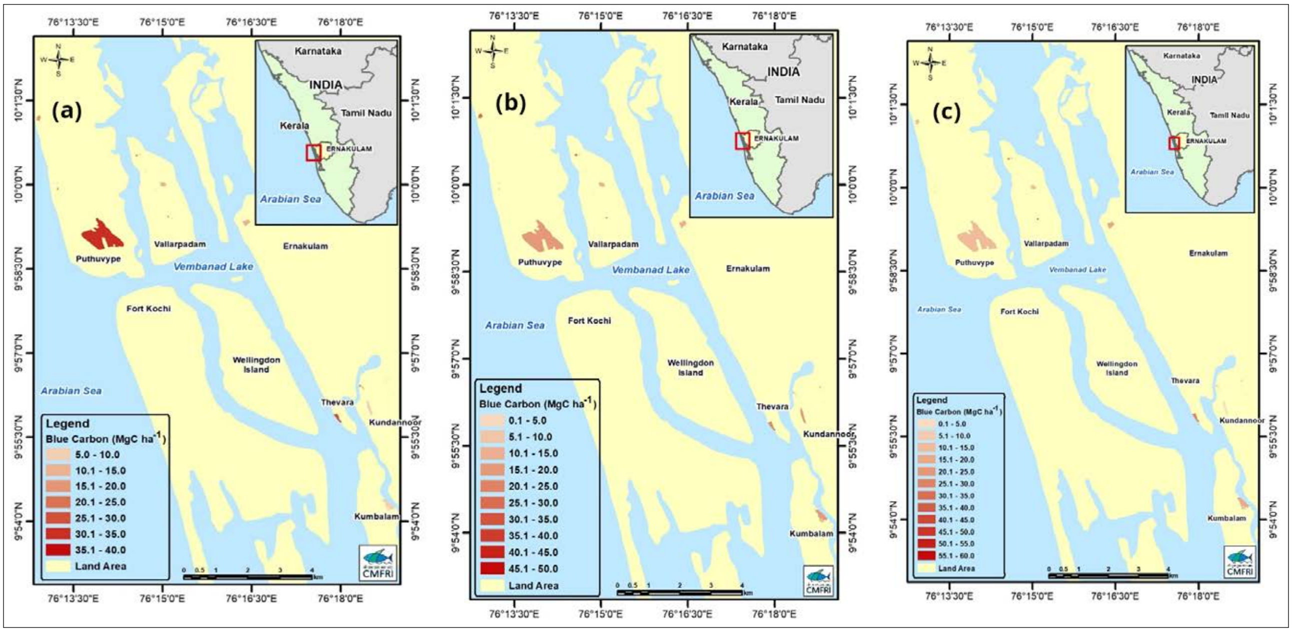

Fig. 5. Map showing layer-wise blue carbon in the sediment of A. *officinalis* at selected locations of Vembanad Lake in post-monsoon; (a) 0-10 cm depth, (b) 10-20 cm depth, (c) 20-30 cm depth

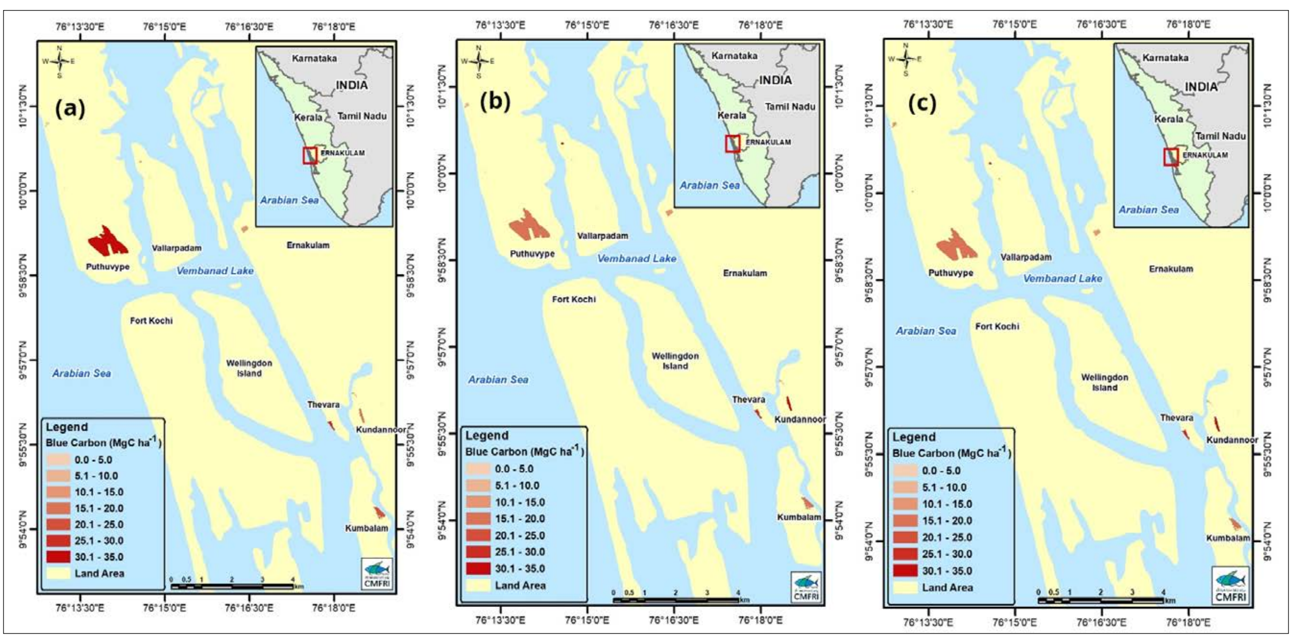

Fig. 6. Map showing layer-wise blue carbon in the sediment of *A. officinalis* at selected locations of Vembanad Lake in pre-monsoon; (a) 0-10 cm depth, (b) 10-20 cm depth, (c) 20-30 cm depth

was 20598.15 Mg C. It was found that the mean blue carbon storage density in the mangrove sediment of the study area is to the tune of 136.09 Mg C/ha which is far below the mean global soil organic carbon stock in the mangrove ecosystem (386 Mg/ha). This finding suggests ample opportunity for more carbon sequestration potential in our coastal mangrove ecosystems through proper management thereby enabling us to contribute more towards climate change mitigation efforts. If we can enhance the blue carbon stock in the Vembanad ecosystem to the world average levels, we can at least sequester an additional amount of 10478.71 Mg C in the study area (Fig. 8).

Measured stock of sediment blue carbon: The samples having core compression and also core sections having water in place of sediment were not taken for laboratory analysis. Wherever intact sediment samples were available in the core, blue carbon stocks up to the maximum available

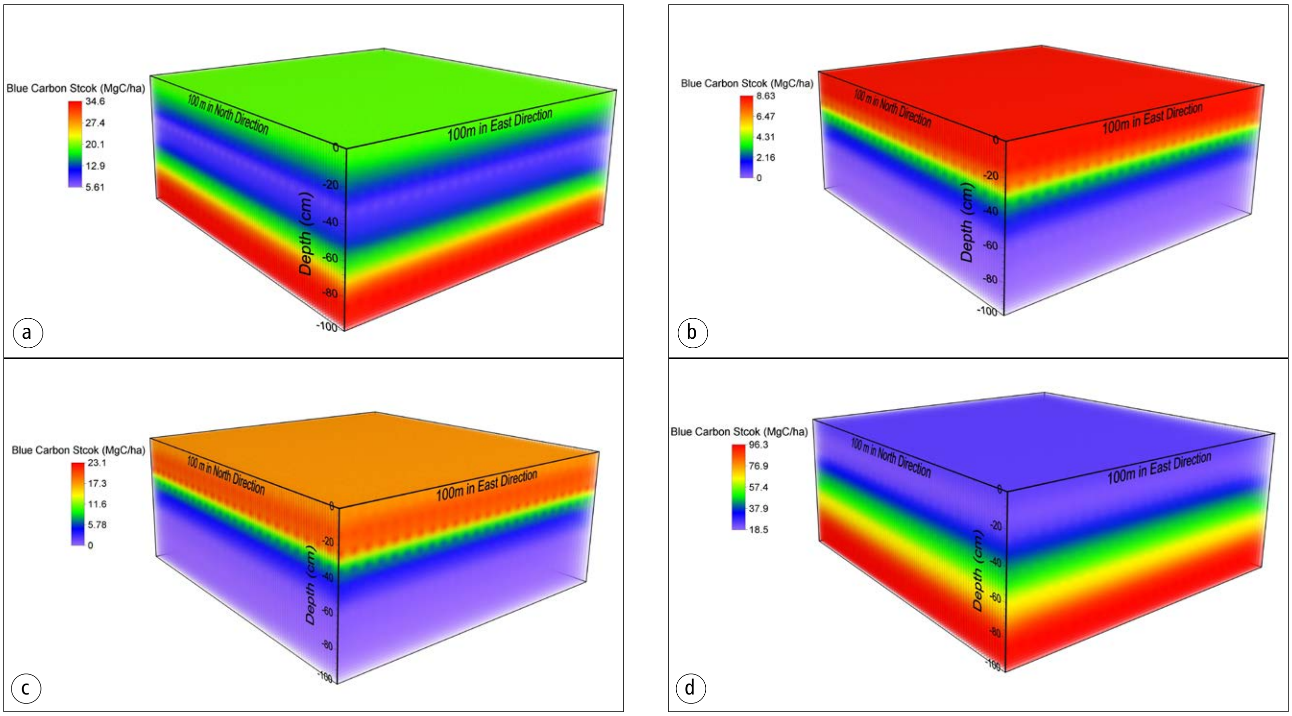

Fig. 7. 3D profile of the sediment blue carbon stock in the mangrove patches of selected locations of Vembanad Lake; (a) Aged Stand, (b) Degraded Stand, (c) Recent Stand, (d) Healthy Stand

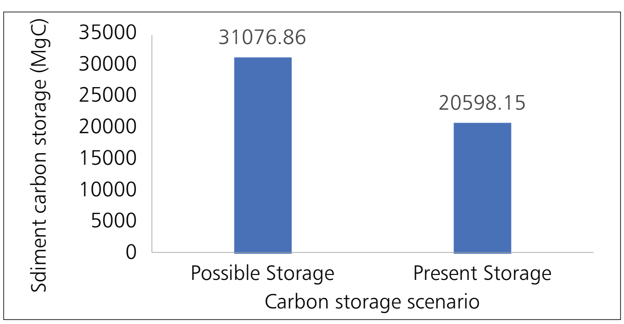

Fig. 8. Comparison of present and possible sediment carbon storage of mangrove patches of selected locations of Vembanad Lake

depth were measured. The values of the measured stock of blue carbon at the maximum possible depth are depicted in Fig. 9.

Total organic carbon (TOC) in sediment: Layer-wise organic carbon in sediment core sections (Fig. 10) of all sampling locations ranged from 0.03 to 6.48% in post-monsoon and the corresponding values in pre-monsoon were 0.18 to 5.81 %. The treatment means of layer-wise organic carbon in sediments ranged from 0.64 (T5 Degraded) to 4.71 % (T4 Healthy) in post-monsoon. In pre-monsoon, the treatment mean values varied from 1.21 (T5 Degraded) to 3.57 % (T4 Healthy).

Dry bulk density of sediment: Layer-wise dry bulk density in sediment core sections (Fig. 11) of all sampling locations ranged from 0.08 to 2.33 Mg/m^3 in post-monsoon and the corresponding values for pre-monsoon were 0.08 to 2.60 Mg/m^3. The treatment means of layer-wise dry bulk density of sediments ranged from 0.54 (T4 Healthy) to 1.41 Mg/m^3 (T3 Recent) in post-monsoon. In pre-monsoon, the mean bulk density in sediment ranged from 0.50 (T3 Recent) to 1.65 Mg/m^3 (T4 Healthy).

Total organic matter in sediment: Layer-wise organic matter in sediment core sections (Fig. 12) of all sampling locations ranged from 0.89 to 11.16 %, 0.05 to 9.47% and 0.31 to 7.09% at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively in post-monsoon and from 0.89 to 10.02 %, 1.12to 7.66 % and 0.31to 7.09% at 0-10 cm, 10-20 cm and 20-30 cm of depths respectively in pre-monsoon.

Ancillary factors considered

Sediment salinity, pH and oxidation reduction potential

The treatment means of layer-wise sediment salinity (Table 2) varied from 6.26 (T3 Recent) to 17.16 ppt (T4 Healthy) in post-monsoon and from 4.08 (T2 Aged) to 15.32 ppt (T4 Healthy) in pre-monsoon. The variation in layer-wise mean sediment pH values (Table 2) was from 6.65 (T1 Control) to 7.55 (T2 Aged) in post-monsoon and from 6.34 (T2 Aged)

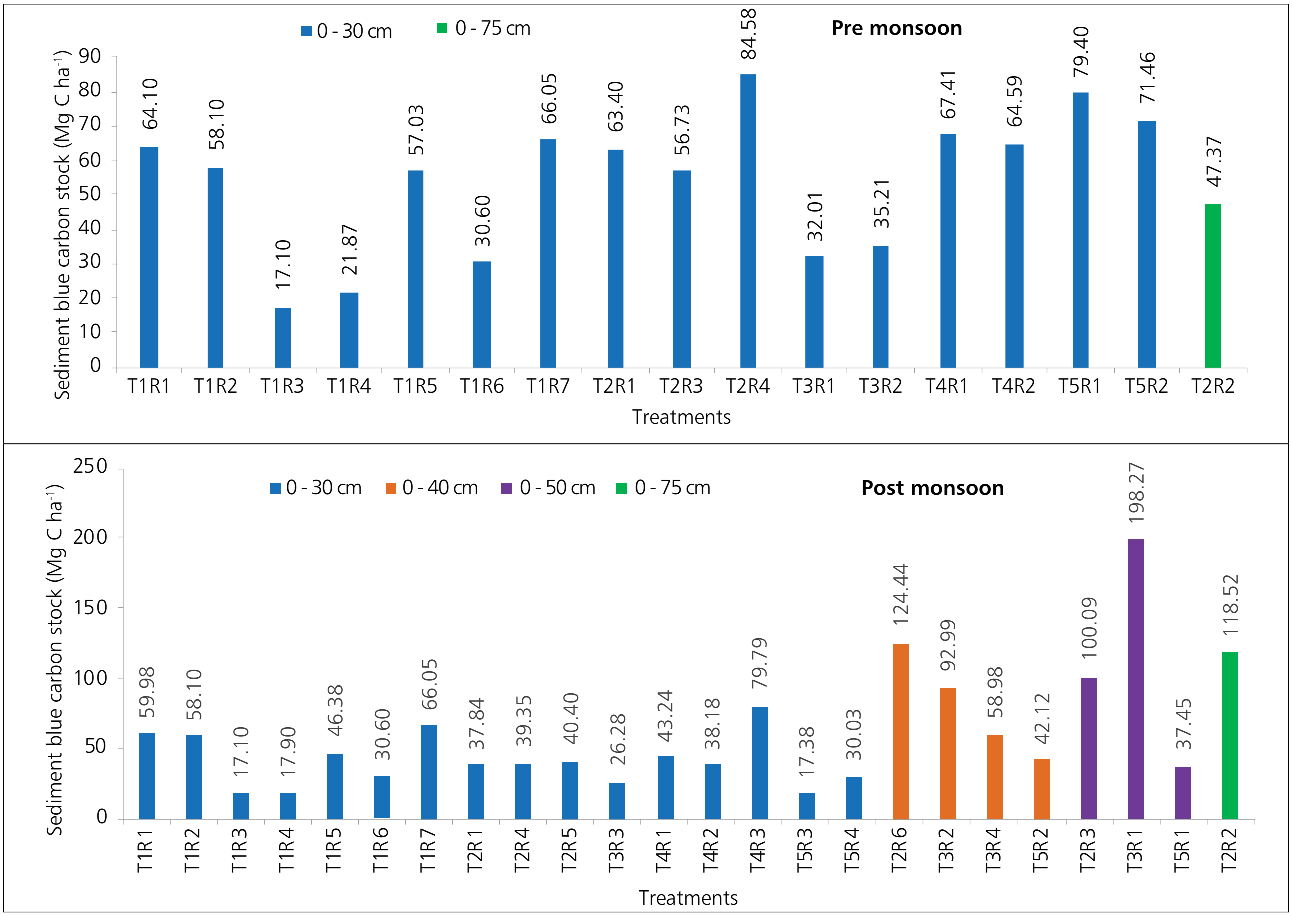

Fig. 9. Measured stock of sediment blue carbon up to maximum possible depth, at selected locations of Vembanad Lake

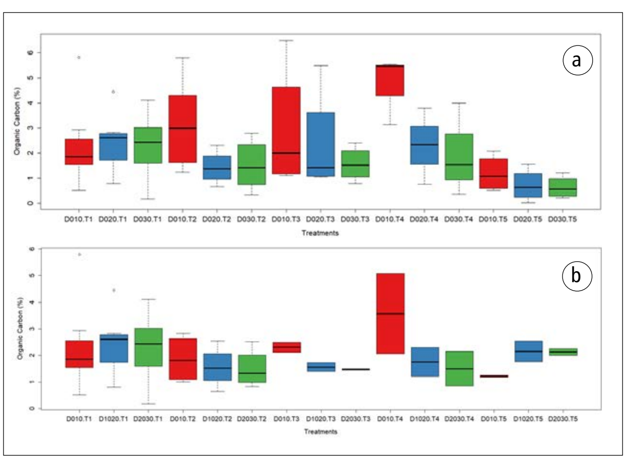

Fig. 10. Layer-wise organic carbon in the sediment of *A. officinalis* at selected locations of Vembanad Lake; (a) Post monsoon, (b) Pre monsoon

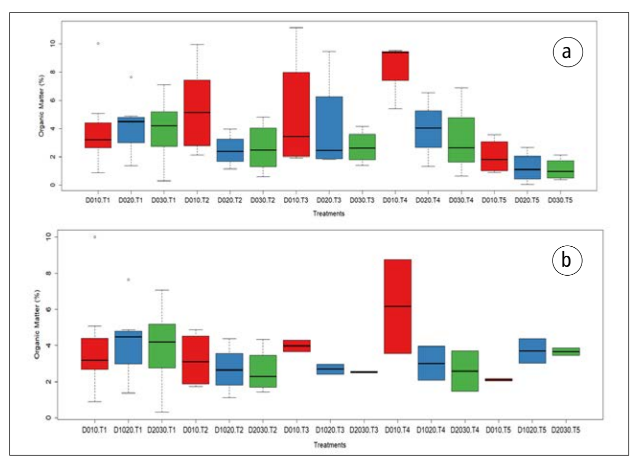

Fig. 11. Layer-wise dry bulk density of sediment of *A. officinalis* at selected locations of Vembanad Lake; (a) Post monsoon, (b) Pre monsoon

to 7.19 (T4 Healthy) in pre-monsoon. The treatment means of the layer-wise oxidation reduction potential of sediments (Eh) varied (Table 2) from -317 mV (T4 Healthy) to -33 mV (T5 Degraded) in post-monsoon. The corresponding variation of Eh in pre-monsoon was from -259 mV (T5 Degraded) to 30 mV (T2 Aged). The highest value of sediment Eh was seen in aged *A. officinalis* (T2) at 20-30 cm core section in pre-monsoon.

Sediment grain size analysis: In post-monsoon, the treatment mean values of layer-wise clay in sediment (Table 2) ranged from 2.16 (T4 Healthy) to 18.54% (T4 Healthy. In pre-monsoon, the

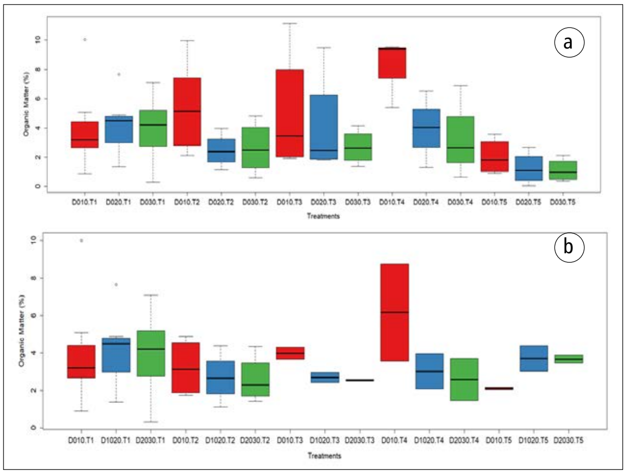

Fig. 12. Layer-wise total organic matter in the sediment of *A. officinalis* at selected locations of Vembanad Lake; (a) Post monsoon, (b) Pre monsoon

corresponding range was from 0.34 (T5 Degraded) to 27.64 % (T2 Aged). The treatment means of layer-wise silt in sediments (Table 2) ranged from 6.94 (T1 Control) to 41.88 % (T4 Healthy) in post-monsoon and from 6.94 (T1 Control) to 22.58 % (T4 Healthy) in pre-monsoon. The variation of treatment means of sand content of sediments (Table 2) in post-monsoon was from 34.75 (T4 Healthy) to 70.44 % (T1 Control). The corresponding pre-monsoon values ranged from 45.4 (T2 Aged) to 70.44 % (T1 Control).

Total carbon, total nitrogen and C/N ratio: The deviation of treatment means of the total carbon content of sediment (Table 2) was from 0.96 (T5 Degraded) to 7.95 % (T4 Healthy) in post-monsoon and from 1.25 (T5 Degraded) to 3.89% (T4 Healthy) in pre-monsoon. Treatment means of the total nitrogen content of sediment (Table 2) varied in post-monsoon from 0.08 (T2 Aged) to 0.35 % (T4 Healthy). In pre-monsoon, the corresponding range was from 0.08 (T5 Degraded) to 0.21% (T4 Healthy). The variation of treatment means of C/N ratio of sediment (Table 2) in post-monsoon was from 3.92 (T5 Degraded) to 48.68 (T4 Healthy). In pre-monsoon, the values ranged from 3.92 (T5 Degraded) to 21.25 (T5 Degraded).

Discussion

The overall mean carbon storage in the *A. officinalis* sediments in selected locations of the Vembanad Lake area was found to be 136.09 Mg C/ha. This value is very little compared to the mean global soil organic carbon stock in the mangrove ecosystem (386 Mg C/ha) (IPCC, 2013), which proposes abundant opportunity to sequester more carbon by way of conservation and restoration of these mangrove ecosystems. Mangrove restoration and conservation are effective tools for increasing carbon storage (Dung *et al*., 2016). Augmented degradation, demands an increased need for mangrove restoration (Upadhyay *et al*., 2015). Natural factors also cause mangrove loss (Jayanthi *et al*., 2018). Carbon burial by mangroves was found to be at the rate of 5 mm/year or 1.74 Mg C/ha (Alongi, 2014).

In the present investigation, ANOVA done for post-monsoon revealed that the blue carbon stock differed significantly among treatments ($p<0.05$) and also among depths ($p < 0.001$). The highest stock (62.47 Mg/ha) was in T4 (Healthy) at 0-30 cm depth. The highest stock was seen in 0-30 cm as the cumulative carbon stock is the sum of layered stocks. Post hoc analysis revealed that there was a highly significant difference between T4 (Healthy) and T5 (Degraded), with higher stock being found in T4 sediment. Weiss *et al.* (2016) found that the mangrove degradation caused a decrease in soil organic carbon stocks to 80–132 Mg C/ha from the original values of 271–572 Mg C/ha in marine mangroves. On degradation, mangrove soils emit CO_2 contributing to climate change (IUCN, 2018; MAP, 2018). One hectare of mangroves on conversion can release 330 mt CO_2e (carbon dioxide equivalent) per hectare per year (Yee, 2010).

Table 2. Treatment-wise variation in selected parameters during post and pre monsoon in *A. officinalis* sediment of Vembanad Lake

No.	Ancillary parameters	Treatment mean values							
		Post-monsoon				Pre-monsoon			
		Min	Treatment	Max	Treatment	Min	Treatment	Max	Treatment
1	Salinity, ppt	6.26	T3	17.16	T4	4.08	T2	15.32	T4
2	pH	6.65	T1	7.55	T2	6.34	T2	7.19	T4
3	Eh, mV	-317.00	T4	-33.00	T5	-259.00	T5	30.00	T2
4	Clay (%)	2.16	T4	18.54	T4	0.34	T5	27.64	T2
5	Silt (%)	6.94	T1	41.88	T4	6.94	T1	22.58	T4
6	Sand (%)	34.75	T4	70.44	T1	45.40	T2	70.44	T1
7	Total carbon (%)	0.96	T5	7.95	T4	1.25	T5	3.89	T4
8	Total nitrogen (%)	0.08	T2	0.35	T4	0.08	T5	0.21	T4
9	C/N ratio	3.92	T5	48.68	T4	3.92	T5	21.25	T5

T1: Control T2: Aged T3: Recent T4: Healthy T5: Degraded

Retrieval of the lost carbon from degraded mangroves will not be achieved in an equitable amount of time, even after restoration (Arifanti *et al.*, 2019).

There was also a significant difference between T3 (Recent) and T5 (Degraded), with higher stock in Recent than in Degraded. For CO_2 sequestration, in the mangrove ecosystem, the pertinent carbon sinks are carbon buried in mangrove sediments as well as the net growth of the mangrove biomass during the growth stage (Patil *et al.*, 2012). As T3 is Recent (<5-year-old) mangroves, they are in the growing stage and contribute to sediment carbon pool. On the other hand, degraded mangroves aid more towards carbon loss from soil.

The treatments differed significantly ($p < 0.05$) for layer-wise blue carbon density, in post and pre-monsoon. The highest value (0.25 Mg/m^3) was seen in T4 (Healthy) at 0-10 cm sediment layer post-monsoon. No significant difference was seen in sub-surface sediment at 10-20 cm and 20-30 cm depths. The top layer (0-10 cm) being more dynamic and exposed to additional physicochemical and biological interactions, was found to be influenced by the seasonal changes. The organic carbon density increased with the age of mangroves and the change in the organic carbon stock was more pronounced in the upper soil layers (Chen *et al.*, 2018; Biswas *et al.*, 2017). With increasing soil depths, the soil carbon stock decreased Nehren and Wicaksono (2018).

The spatial maps indicated higher amounts of layer-wise organic carbon density in post-monsoon, compared to pre-monsoon. In post-monsoon, there was a depth-wise increase in layer-wise organic carbon density, though it was not statistically significant. This stratification in layered carbon showing a depth-wise increase was seen only in post-monsoon. This may be due to the higher amount of rainfall received in the northeast monsoon which would have facilitated the export of carbon downwards. It was also observed that the cumulative stock of carbon in sediment up to 30 cm depth was higher in post-monsoon than in pre-monsoon. Kathiresan *et al.* (2013) found that the rate of carbon sequestration was 7.3-fold higher in post-monsoon, than that in pre-monsoon. The carbon accumulating in the mangrove soils need not be full of the local production by mangroves, but organic matter can be brought in, during high tide or by runoff (Patil *et al.*, 2012). In the present study, the mean local (district level) rainfall (IMD, 2018) during post-monsoon (October-November 2017) was 473.7 mm and during pre-monsoon (February-March 2018), it was 39.5 mm, which indicates carbon addition by run-off in post monsoon. A significant ($p < 0.05$) correlation between annual rainfall and total organic carbon storage in mangrove soils was observed (Perera and Amarasinghe, 2019; Etemadi *et al.*, 2018; Schile *et al.,* 2017; Sanders *et al.*, 2016; Osland *et al.*, 2018).

The 3-D profile depiction of the sediment carbon data on Vembanad Lake Mangroves derived from the present study indicated the loss of sediment carbon from degraded mangroves. The climate change mitigation potential of healthy mangroves, by way of their higher carbon sequestration capability, was also distinct. Similarly, the aged mangroves in this estuarine region showed higher carbon sequestration ability, compared to their recent counterparts. The conservation and restoration of estuarine mangroves are of paramount importance in the climate change mitigation aspect, as the estuarine mangroves were reported to have more soil carbon stock compared to those oceanic mangroves (Duncan *et al.*, 2016; Nehren and Wicaksono, 2018). It was also seen that the highest carbon stock was at 0-50 cm depth in post-monsoon. The data revealed that the depth-wise variation in carbon stock was not according to any obvious trend. The factors controlling depth-wise variation of soil carbon stock in mangroves is a complex dynamic function affected by many environmental agents and eventful disturbances (Alongi, 2008).

In the present research, the highest value of total organic carbon in sediment was seen in healthy *A. officinalis* (T4) at 0-10 cm post-monsoon. ANOVA for layer-wise organic carbon in post-monsoon revealed highly significant variation ($p<0.01$). According to Batley and Simpson (2016), the total organic carbon indicates the total amount of oxidizable organic material. Depth-wise variation in organic carbon in sediment layers was also significant ($p<0.05$). The top layer (0-10 cm) was having the highest content of organic carbon of all the treatments. Post hoc analysis pointed out that 0-10 cm and 20-30 cm depths differed significantly in the organic carbon content, indicating a depth-wise decrease in mean organic carbon; as observed by Mitra *et al.* (2008) and Pachpande and Pejaver (2015). The mangrove ecosystems exhibited a higher capacity for organic matter production and storage in surface soil than that in terrestrial ecosystems (Matsui *et al.*, 2015).

During blue carbon stock estimation, the bulk density is used for the conversion of organic carbon concentrations to mass per soil area at a chosen depth (Avelar *et al.*, 2017). In the present analysis, the highest value of bulk density was found for the sediment of recent *A. officinalis* (T3) at a 20-30 cm core section post-monsoon. Depth-wise variation of bulk density of sediment layers was highly significant ($p<0.01$). The bulk density was also seen negatively correlated with total organic carbon (-0.56**). The increased bulk density in the deeper layer implies the increased compaction of sediment with depth. In mangrove sediments, the bulk density depends upon the relative proportion of sand, silt and clay as well as the specific gravity of solid organic and inorganic particles and the porosity of the soil (Mitra *et al.,* 2008, 2012).

The layer-wise total organic matter in the sediment, in post-monsoon, varied significantly treatment-wise ($p<0.01$) and depth-wise ($p<0.05$). The top layer (0-10 cm) was having the highest content of organic matter in all treatments except for the control. The highest value of total organic matter was seen in the sediment of healthy *A. officinalis* (T4) at 0-10 cm. The variation in total organic matter was similar to that of total organic carbon in sediment, as the value of the organic matter in sediment was derived from the organic carbon content based on the empirical relationship between them.

In pre-monsoon, the highest value of sediment salinity was seen in healthy *A. officinalis* (T4) at 20-30 cm. In the present study, soil salinity was positively correlated (Table 2) with the silt content of soil (0.61***) and also with pH (0.62***). Rozainah *et al.* (2018) demonstrated that mangrove forests differed in biomass and carbon storage capacity as per changes in their location due to variable salinity, soil texture and water flow.

There was no clear-cut trend in the variation of sediment pH in the present study. The mangrove soil seemed to be more in the neutral to alkaline range compared to the control. This was in concordance with the finding of Phang *et al.* (2015), within the range of pH optima for *A. officinalis*. The pH was found positively correlated (Table 2) with silt (0.75***) and salinity (0.62***), indicating pH regulation by the acidic/basic salts present in the soil and also the base saturation of the soil.

The Eh in post-monsoon showed a reducing condition in sediment. This can be attributed to the submerged condition of the soil post-monsoon. In all mangrove treatments, there was an increasing trend of Eh towards subsurface layers of sediment in post-monsoon as a consequence of the decrease in organic carbon content. The subsurface layers of sediment showed an inclination towards an oxidizing condition in pre-monsoon. The seasonal difference can be due to the more aerated condition of the soil in pre-monsoon, sediment having more exposure rather than submergence, which favoured decomposition of organic matter. A similar result was obtained by Kathiresan *et al.* (2014). The correlations of Eh with organic matter (-0.56**), organic carbon (-0.56**) and C/N ratio (-0.60***), further substantiated the relation between Eh and organic matter decomposition in mangrove sediment.

The highest value of clay was seen in the sediment of healthy *A. officinalis* (T4) at 0-10 cm in post-monsoon and the highest value of silt in the sediment of healthy *A. officinalis* (T4) at 0-10 cm in pre-monsoon. The highest value of sand was observed in the sediment of control (T1) at 0-10 cm in post-monsoon. The sediment with at least 11% clay in the top layer shows good growth of mangroves (Prema *et al.,* 2013). Mangroves having significantly lower soil carbon pools were observed by Kauffman and Bhomia (2017) in coarse-textured soils.

There was no obvious trend in depth-wise variation of total carbon and total nitrogen in sediment among treatments in both seasons. Mangrove soils are in general rich in total carbon and total organic carbon. Total carbon was 98.2% higher in mature mangroves and 41.8% higher in planted mangroves than that in non-mangrove soil (Kathiresan *et al.,* 2014). There was a depth-wise decreasing trend in the C/N ratio in sediment in T4 and T3 in both seasons. The carbon and nitrogen concentrations were lower at all sediment depths in shorter mangroves, compared to medium ones, while taller mangroves had still

Table 3. Correlation matrix showing the interrelationship of various parameters during the study period

Correlations	BCstock	BClayer	OClayer	BDlayer	OMlayer	TClayer	TNlayer	CNratioLR	Ehlayer	Sandlayer	Siltlayer	Claylayer	Sallayer
BCstock													
BClayer	0.43*												
OClayer	-0.13	0.51**											
BDlayer	0.60***	0.33	-0.56**										
OMlayer	-0.13	0.51**	1.00***	-0.56**									
TClayer	0.2	0.34	0.60***	-0.26	0.60***								
TNlayer	0.27	-0.01	-0.03	0.08	-0.03	0.48**							
CNratioLR	-0.15	0.40*	0.75***	-0.40*	0.75***	0.28	-0.58***						
Ehlayer	0.17	-0.33	-0.56**	0.26	-0.56**	-0.11	0.31	-0.60***					
Sandlayer	-0.25	-0.29	-0.18	-0.06	-0.18	-0.57**	-0.04	-0.24	-0.14				
Siltlayer	0.25	0.21	0.06	0.23	0.06	0.39*	0.03	0.23	0.00	-0.51**			
Claylayer	-0.27	-0.03	0.37*	-0.47**	0.37*	-0.03	-0.07	0.17	-0.07	0.03	-0.49**		
Sallayer	0.1	0.1	0.2	0.05	0.2	0.3	-0.04	0.27	-0.41*	-0.14	0.61***	-0.26	
pHlayer	0.14	0.22	0.16	0.09	0.16	0.35	-0.03	0.34	-0.24	-0.17	0.75***	-0.53**	0.62***

***$p < .001$; ** $p < .01$; * $p < .05$

higher soil nitrogen and carbon concentrations (Kauffman and Bhomia, 2017). The carbon-nitrogen relationship in mangrove sediments indicated that carbon was the main source of nitrogen (Matsui *et al.*, 2015). Due to the high C/N Ratio, in mangrove soils, sometimes the N regulates the mangrove growth (Weiss *et al.*, 2016).

Correlation analysis (Table 3) revealed that layer-wise blue carbon was highly significantly correlated with total organic carbon and organic matter in the sediment layer ($p<0.01$) positively. Blue carbon stock was found to be correlated ($p<0.05$) with layer-wise bulk density. There was also a positive correlation between layer-wise blue carbon and C/N ratio in the sediment ($p<0.05$). Kathiresan *et al.* (2014) found a significant positive correlation between mangrove sediment carbon and with C/N ratio of sediment. The C/N ratio is regularly used as an indicator of the organic matter sources in aquatic sediments. Sediments of marine mangroves had a higher C/N ratio when compared with estuarine mangroves (Weiss *et al.*, 2016). The present study suggests total organic carbon and C/N ratio of the sediment as possible predictive indicators of blue carbon in mangrove sediments with further investigation in depth.

Conclusion

There is ample opportunity to sequester more carbon in the coastal mangrove ecosystems of Vembanad Lake through the conservation and/or restoration of *A. officinalis.* The results of this investigation can be used as baseline data for related future studies in this region, in addition to its usefulness for the preparation of situation-specific policy guidelines for climate change mitigation efforts. Further, in-depth investigations need to be done to assess the sediment carbon stock and carbon sequestration potential of blue carbon ecosystems in Vembanad Lake. The total organic carbon and C/N ratio are possible predictive indicators of blue carbon stock in sediment, which need to be reinstated with further analysis.

Acknowledgements

The authors are grateful to the Director, ICAR-CMFRI for providing the facilities and support for the smooth conduct of this study, and to the Head, Fishery Environment Management Division for scrutinizing the manuscript and offering constructive suggestions for improvement.

References

Alongi, D. M. 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuar. Coast. Shelf Sci.,* 76: 1-13.

Alongi, D. M. 2014. Carbon cycling and storage in mangrove forests. *Ann. Rev. Mar. Sci.*, 6: 195-219.

Arifanti, V. B., J. B. Kauffman, D. Hadriyanto, D. Murdiyarso and R. Diana. 2019. Carbon dynamics and land use carbonfootprints in mangrove- converted aquaculture: the case of the Mahakam Delta, Indonesia. *For. Ecol. Manag.,* 432: 17-29.

Avelar S., T. S. Van der Voort and T. I. Eglinton. 2017. Relevance of carbon stocks of marine sediments for national greenhouse gas inventories of maritime nations. *Carbon Bal. Manag.,* 12: 1-10.

Batley, G. and S. Simpson. 2016. Sediment quality assessment: a practical guide. (Eds), eBook. CSIRO PUBLISHING. https://www.publish.csiro.au/book/7383

Biswas, S., S. Zaman and A. Mitra. 2017. Soil Characteristics of Indian Sundarbans: The Designated World Heritage site. *Sci. J. Biomed. Eng. Biomed Sci.*, 1(2): 053-059.

Boyd, C. E. and C. S. Tucker. 1992. *Water quality and pond soil analysis for Aquaculture,* Alabama Agricultural Experiment station. Auburn University: 13 pp.

CCC (Climate Change Commission). 2017. CCC pushes for the protection and conservation of coastal blue carbon. http://climate.gov.ph/knowledgebank/newsroom/press-release/379-ccc-pushes-for-the-protection-and-conservationof-coastal-blue-carbon-ecosystems Downloaded on 08 December 2017.

Chen, G., M. Gao, B. Pang, S. Chen and Y. Ye. 2018. Top-meter soil organic carbon stocks and sources in restored mangrove forests of different ages. *For. Ecol. Manag.,* 422: 87–94.

Duncan, C., J. H. Primavera, N. Pettorelli, J. R. Thompson, R. J. A. Loma and H. J. Koldewey. 2016. Rehabilitating mangrove ecosystem services: A case study on the relative benefits of abandoned pond reversion from Panay Island, Philippines. *Mar. Pollut. Bull.*, 109: 772-782.

Dung, L. V., N. T. Tue, M. T. Nhuan and Koji Omori. 2016. Carbon storage in a restored mangrove forest in Can Gio Mangrove Forest Park, Mekong Delta, Vietnam. *For. Ecol. Manag.,* 380: 31-40.

Etemadi, H., J. M. Smoak and C. J. Sanders. 2018. Forest migration and carbon sources to Iranian mangrove soils. *J. Arid Environ.,* 157: 57-65.

FAO (Food and Agricultural organization of the United Nations). 1976. *Soil bulletin No:10, Physical and chemical methods of soil and water analysis:* 275 pp.

George, G., P. Krishnan, K. G. Mini, S. S. Salim, P. Ragavan, S. Y. Tenjing, R. Muruganandam, S. K. Dubey, A. Gopalakrishnan, R. Purvaja and R. Ramesh. 2018. Structure and regeneration status of mangrove patches along the estuarine and coastal stretches of Kerala, India. *J. For. Res.*, p. 1-12.

Hesse, P. R.1971*. A textbook of soil chemical analysis.* Chemical publishing Co Inc. New York, 520 pp.

Howard, J., S. Hoyt, K. Isensee, M. Telszewski and E. Pidgeon. 2014. *Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses*. Conservational International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature, Arlington. http://www.thebluecarboninitiative.org/manual/2014

IMD (India Meteorological Department). 2018. *Daily weather report*, Kerala and Lakshadweep 1st October and November 2017-1st February and March 2018.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: the physical science basis. In: Solomon, S., Qin, D. and Manning, M. (Eds). *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, NY: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change). 2013. Coastal Wetlands. In: 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (eds. Alongi, D, Karim, A, Kennedy, H, Chen, G, Chmura, G, Crooks, S *et al*.). *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, and New York, NY: Cambridge University Press.

IUCN (International Union for Conservation of Nature). 2018. Blue carbon. https://www.iucn.org/resources/issues-briefs/blue-carbon Downloaded on 31 May 2018.

Jackson, M. L. 1958. *Soil Chemical Analysis*. Engle-wood Cliffs. *NT Prentice Hall Inc. J. Plant. Nutr. Soil. Sci.*, 85 (3): 251-252.

Jayanthi, M., S. Thirumurthy, G. Nagaraj, M. Muralidhar and P. Ravichandran. 2018. Spatial and temporal changes in mangrove cover across the protected and unprotected forests of India. *Estuar. Coast. Shelf. Sci.,* 213: 81-91.

Kaladharan, P., S. Veena and E. Vivekanandan. 2009. Carbon sequestration by a few marine algae: observation and projection. *J. Mar. Biol. Ass. India,* 51(1): 107-110.

Kaladharan, P., K. Vijayakumaran, L. Edward Loveson, S. Lavanya and Dash, Biswajit. 2021. Blue carbon stock of seagrass meadows of Chilika and Pulicat lakes along the Eastern Coast of India. *Fish. Technol.*, 58: 143-146.

Kaladharan, P., P. U. Zacharia, S. Thirumalaiselvan, A. Anasu Koya, S. Lavanya and Batcha, S. M. Sikkander. 2020. Blue carbon stock of the seagrass meadows of Gulf of Mannar and Palk Bay off Coromandel Coast, south India. *Indian J. Fish.*, 67(4): 149-153.

Kathiresan, K., R. Anburaj, V. Gomathi and K. Saravanakumar. 2013. Carbon sequestration potential of *Rhizophora mucronata* and *Avicennia marina* as influenced by age, season, growth and sediment characteristics in southeast coast of India. *J. Coastal Conserv.,* 17(3): 397-408.

Kathiresan, K., V. Gomathi, R. Anburaj and K. Saravanakumar. 2014. Impact of mangrove vegetation on seasonal carbon burial and other sediment characteristics in the Vellar-Coleroon estuary, India. *J. For. Res.* 25(4): 787-794.

Kathiresan, K., R. Narendran, B. Balasubramaniyan, T. Ramanathan and N. Rajendran. 2021. Carbon sequestration and storage in planted mangrove stands of *Avicennia marina*, *Reg. Stud. Mar. Sci.*, 43(3): 101701.

Kauffman, J. B. and R. K. Bhomia. 2017. Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: Global and regional comparisons. *PLoS ONE,* 12(11): e0187749.

MAP (Mangrove Action Project). 2018. Mangrove action project 2013-2018. http://mangroveactionproject.org/issues/climate-change Downloaded on 02 August 2018.

Matsui, N., W. Meepol and J. Chukwamdee. 2015. Soil organic carbon in mangrove ecosystems with different vegetation and sedimentological conditions. *J. Mar. Sci. Eng.*, 3(4): 1404-1424.

Mcleod, E., G. L. Chmura, S. Bouillon, R. Salm, M. Björk, C. M. Duarte, C. E. Lovelock, W. H. Schlesinger and B. R. Silliman. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Front. Ecol. Environ.,* 9(10): 552–560.

Mitra, A., S. C. Santra and J. Mukherjee. 2008. Distribution of actinomycetes, their antagonistic behaviour and the physico-chemical characteristics of the world's largest tidal mangrove forest. *Appl. Microbial. Biotechnol.,* 80(4): 685-695.

Mitra, A., K. Banerjee and S. Sett. 2012. Spatial variation in organic carbon density of mangrove soil in Indian Sundarbans. *Natl. Acad. Sci. Lett.,* 35(3): 147-154.

Mogalekar, H. S., G. Adnankhan, C. P. Ansar, N. N. Raman and A. Devkate. 2015. Temporal variation in the hydrobiology of Vembanad Lake at Panangad Kumbalam mangrove patches of Kochi, Kerala. *Res. J. Anim. Vet. Fish. Sci.*, 3: 1-7.

Osland, M. J., C. A. Gabler, J. B. Grace, R. H. Day, M. L. McCoy, J. L. McLeod, A. S. From, N. M. Enwright, L. C. Feher, C. L. Stagg and S. B. Hartley. 2018. Climate and plant controls on soil organic matter in coastal wetlands. *Glob. Chang. Biol.*, 24: 5361-5379.

Nehren, U. and P. Wicaksono. 2018. Mapping soil carbon stocks in an oceanic mangrove ecosystem in Karimunjawa Islands, Indonesia. *Estuar. Coast. Shelf. Sci.,* 214: 185-193.

Pachpande, S. C. and M. Pejaver. 2015. Natural carbon sequestration by dominant mangrove species *Avicennia marina* var. Accutissima ex Staf and Moldenke ex Moldenke found across Thane Creek, Maharashtra, India. *Int. J. Sci. Eng. Res.,* 6: 1162-1165.

Patil, V., A. Singh, N. Naik, U. Seema and B. Sawant. 2012. Carbon sequestration in Mangrove Ecosystems. *J. Environ. Res. Develop.,* 7(1A): 576-583.

Perera, K. A. R. S. and M. D. Amarasinghe. 2019. Carbon sequestration capacity of mangrove soils in micro tidal estuaries and lagoons: A case study from Sri Lanka. *Geoderma,* 347: 80–89.

Pendleton, L., D. C. Donato, B. C. Murray, S. Crooks, W. A. Jenkins, S. Sifleet, C. Craft, J. W. Fourqurean, J. B. Kauffman, N. Marbà and P. Megonigal. 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE*, 7(9): p.e43542.

Phang, V. X., L. M. Chou and D. A. Friess. 2015. Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. *Earth. Surf. Process. Landf.,* 40(10): 1387-1400.

Prema, D., P. S. Anilkumar, K. K. Valsala, L. R. Khambadkar, R. Sharma, A. Mohan, J. Bose and V. Kripa. 2013. Sediment quality evaluation towards developing scientific restoration protocol for mangroves. *Mar. Fish. Inf. Serv. T & E Ser.,* 212: 3-4.

Rozainah, M. Z., M. N. Nazria, A. B. Sofawia, Z. Hematic and W. A. Juliana. 2018. Estimation of carbon pool in soil, above and below ground vegetation at different types of mangrove forests in Peninsular Malaysia. *Mar. Pollut. Bull.,* 137: 237-245.

Sanders, C. J., D. T. Maher, D. R. Tait, D. Williams, C. Holloway, J. Z. Sippo and I. R. Santos. 2016. Are global mangrove carbon stocks driven by rainfall? *J. Geophys. Res. Biogeosci.*, 121: 2600–2609.

Schile, L. M., J. B. Kauffman, S. Crooks, J. W. Fourqurean, J. Glavan and J. P. Megonigal. 2017. Limits on carbon sequestration in arid blue carbon ecosystems. *Ecol. Appl.*, 27: 859–874.

Varghese, Molly., K. Vinod, K. R. Aju, K. M. Sreekumar, P. A. Thobias, C. P. Ansar, Gokul Vijayan, M. Nikhiljith and K. K. Joshi. 2021. Biomass and carbon stocks in two mangrove patches of Chettuva Estuary, south-west coast of India. *J. Mar. Biol. Ass. India,* 63(1): 122-127.

Vidyasagaran, K. and V. K. Madhusoodanan. 2014. Distribution and plant diversity of mangroves in the west coast of Kerala, India. *J. Biodivers. Environ. Sci.*, 4: 38-45.

Vinod, K., P. K. Asokan, P. U. Zacharia, C. P. Ansar, Gokul Vijayan, A. Anasu Koya, V. A. Kunhikoya and M. Nikhiljith. 2020. Assessment of Biomass and Carbon Stocks in Mangroves of Thalassery Estuarine Wetland of Kerala, South West Coast of India. *J. Coast. Res.*, 86: 209-217.

Vinod, K., A. Koya, V. Koya, P. Silpa, P. Asokan, P. U. Zacharia and K. K. Joshi. 2018. Biomass and carbon stocks in mangrove stands of Kadalundi Estuarine Wetland, south-west coast of India. *Indian J. Fish.,* 65(2): 89-99.

Upadhyay, R., N. Joshi, A. C. Sampat, A. K. Verma, A. Patel, V. Singh, J. Kathota and M. H. Kalubarme. 2015. Mangrove Restoration and Regeneration Monitoring in Gulf of Kachchh, Gujarat State, India, using remote sensing and geo-informatics. *Int. J. Geosci.*, 6: 299-310.

Weiss, C., J. Weiss, J. Boy, I. Iskandar, R. Mikutta and G. Guggenberger. 2016. Soil organic carbon stocks in estuarine and marine mangrove ecosystems are driven by nutrient co-limitation of P and N. *Ecol. Evol.*, 6(14) : 5043-5056.

Yee, S. M. 2010. REDD and BLUE Carbon: Carbon payments for mangrove conservation, MAS. *Mar. Biodivers. Conserv. Capstone Project,* 13 pp.