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Soil organic carbon stock in natural and restored mangrove forests in Pichavaram south-east coast of India

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Mangrove ecosystem is one of the important coastal ecosystems providing ecological security of the coastal area and livelihood security to the coastal fishermen. Besides it plays an important role in carbon sequestration as large amount of carbon is stored in the below ground biomass. The role of mangrove restoration in carbon stocking has not been studied comprehensively either globally or nationally. The aim of the present study is to quantify the soil organic carbon stock and carbon sequestration rate of the different age groups of restored and natural stands of Pichavaram mangroves forest. The soil organic carbon stock of the upper soil layer (0–90 cm) of six different sites from natural mangrove stands, 21years, 17 years, 16 years, 15 years and 12 years old stands were 146.1(Mg C ha^{-1}), 99.29 (Mg C ha^{-1}), 93.18 (Mg C ha^{-1}), 57.41 (Mg C ha^{-1}), 95.54 (Mg C ha^{-1}) and 84.84 (Mg C ha^{-1}), respectively. Carbon sequestration rate of Pichavaram mangrove forests ranged from 2.33 to 4.44 g C m^{-2} $year^{-1}$. The result of the study reveals that soil organic carbon stock and burial rate were high in natural mangrove area than the restored areas. In this regard, restoration and rehabilitation of mangroves is required for preserving the ecologically important mangroves ecosystem to mitigate the impacts of climate change.

[Keywords: Mangroves; Resorted stands; Natural stand; Soil organic carbon; Carbon sequestration]

Introduction

Mangrove forests are a dominant feature of tropical and subtropical coastlines mainly between 30^{o}N and 30^{o}S. The area covered by mangrove forests is only a small fraction of about 0.5% of global coastal areas[1]. Mangrove wetland has high rates of productivity and low decomposition processes. Mangrove soils store about 218 ± 72 Tg C per year globally[2] and it sinks 3-5 times more carbon than terrestrial forest[3,4]. The burial rates of organic carbon in mangroves soil through surface accretion is about 1.32 to 2.03 Mg C ha^{-1} $years^{-1}$, globally[5]. Carbon storage in mangrove forests is largely in the below ground stocks.

Carbon inputs come from three different sources: Allochthonous contribution as terrestrial riverine input, coastal waters by sea currents and tidal waters, and *in situ* autochthonous productions in mangrove forest from litter fall and soil roots. This organic carbon in soil under mangrove forest can store up to 49-98% of the total ecosystem carbon due to rapid rates of productivity and sedimentation[3,6]. Apart from this, mangrove ecosystem also provides various ecological services in terms of protection from natural calamities, such as tsunami, storm surges, and tropical cyclones. In addition, it serves as a breeding and spawning ground for many commercially important fishery resources, and thereby supports main livelihood source for mangrove dependent fishermen[7]. Globally, the mangrove area has reduced less than 50% of the original total cover due to severe pressure from both anthropogenic activities and climate change scenarios[8]. The sea level rises, increasing greenhouse gases emission and tropical storm surge are the key climate change factors that are threatening the mangrove ecosystem[9]. Since 1970s, the Sundarban mangroves have lost 17,000 ha due to sea level rise[10]. Anthropogenic pressures such as overharvesting for timber and fuel-wood production, reclamation for aquaculture, river damming and salt pond construction alter water salinity level account for the mangrove losses[11]. However, during the last three decades, several countries are implementing mangrove rehabilitation and restoration programmes effectively to reverse the loss in mangrove forest cover.

As a result of mangrove rehabilitation programme in India, the mangrove cover has increased from 4046 (1987) to 4740 (2015) sq. km[12,13] and is now accounting for nearly 3% of the world's mangrove vegetation and 0.14% of the country's total geographical area. The M S Swaminathan Research Foundation (MSSRF), Chennai, is the pioneer in the mangrove conservation research in India as well in Asian countries. MSSRF launched the restoration programme during early 1990s and restored the degraded areas along the east and west coast states with active support from the Government of India and various international research agencies. Mangrove rehabilitation was initiated in the Pichavaram mangrove forest (Tamil Nadu) with the collaboration of local community and State forest department. The present investigation was to assess the baseline soil organic carbon stock in the natural as well as different age groups of the restored mangrove stands of the Pichavaram Mangrove forest. Quantification of soil organic carbon in the natural and restored mangrove is limited[14]. Hence, the present study aims to fill the existing knowledge gap in the soil carbon sequestration rate in the mangrove forest of Pichavaram, south-east coast of India.

Materials and Methods

Study area

The present study was carried out in the Pichavaram mangrove wetland located between Vellar and Coleroon estuaries of the Cauvery delta (Lat. 11^0 20'N; Long 79^0 55'E) in the south-east coast of peninsular India (Fig. 1). The forests occupy an area of about 1400 ha with dense mangroves in about 700 ha. It consists of about 51 small islands colonized by mangrove vegetation. The climate in Pichavaram is sub-humid with very warm summer (> 30 ^{o}C) with an average annual rainfall of about 1310 mm. There are 12 species of true mangroves present in the Pichavaram mangrove wetland[7]. The distribution pattern of the true mangrove species shows two distinct zones: *Rhizophora* spp. zone and *Avicennia* spp. zone. *Rhizophora* zone is found in the fringe areas all along the tidal waterways including small creeks. The width of this zone is very narrow, ranging from 6 to 18 m. *Avicennia* zone is found immediately next to *Rhizophora* zone and its width varies from 60 to 80 m, depending upon the size of the islands[15].

Locations of sampling

Soil Samples were collected during June-July 2017 in six different locations of the natural and restored mangrove forest areas. One natural mangrove stand (Site—1) and five different age groups (Site—2-6) of restored mangrove stands (*i.e.* 21 year, 17 year, 16 year, 15 year, and 12 year-old stands) were fixed (Fig. 1). All these restoration activities were started between 1993 and 1995 in the Pichavaram mangrove

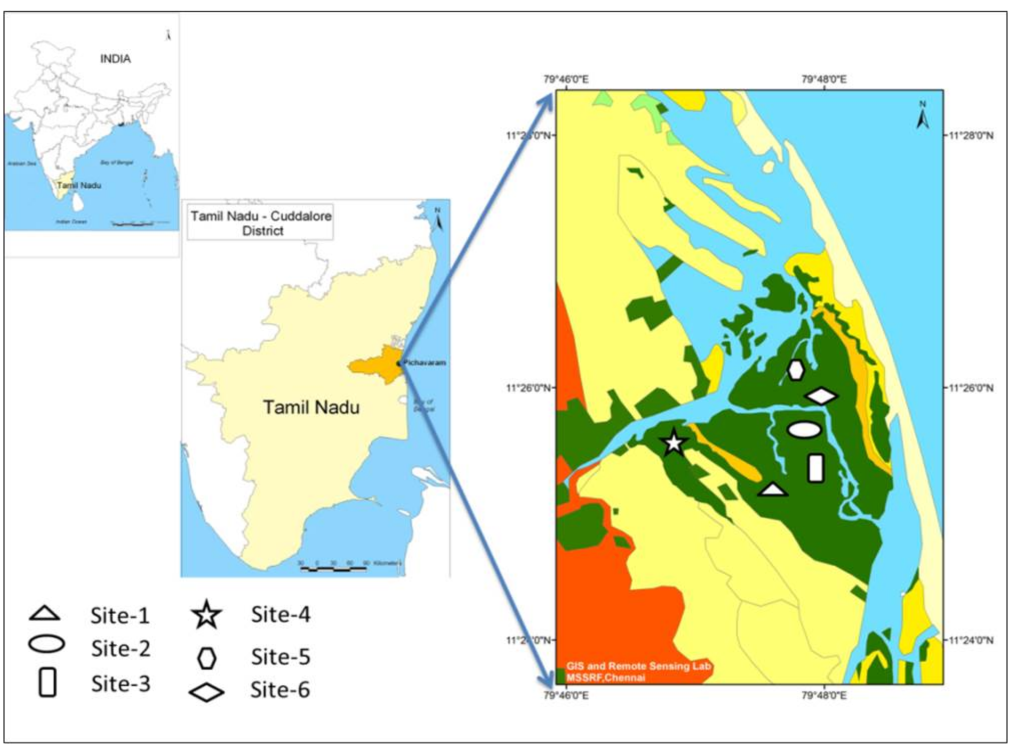

Fig. 1 — The study areas Site 1 represent natural mangrove stand and five different age groups, Site 2-6 of restored mangrove stands.

forest employing canal method of restoration by MSSRF in collaboration with the Tamil Nadu forest department and local communities under Joint Mangrove Management (JMM).

Soil analysis

The soil samples were collected in the landward side, dense and seaward mangroves stands from a depth of 0-15 cm, 15-30 cm, 30-60 cm and 60-90 cm using a stainless steel corer. In each of the location, 10 sampling sites were selected to assure representative sample in each of the different age groups and natural mangrove stands. Leaf area index (LAI) was measured at each site in the four different directions using a portable LAI-2200 plant canopy analyzer (Li-Cor Inc., USA). The tree height was measured using telescopic pole at each sampled site. The collected soil samples were kept in plastic bags and brought to the laboratory for further analysis. The following properties were measured to obtain basic descriptive data of the soils: Soil pH and Salinity were measured made *in-situ* by dipping digital pH (Model-HI99121, Hanna instruments) and EC meter (Model-HI98331, Hanna instruments) probe directly to collected soils. The composition of soil texture in the sediment samples were determined by the combined sieving and pipette method of Krumbein and Pettijohn (1938). The nitrates were estimated by “Cd” redactor method. Total phosphorus (P) and soil organic carbon (SOC) were measured by Kjeldhal, Olsen and Walkely & Black method, respectively. Bulk density (SDB) was determined by dividing the oven-dry soil sample by the volume of the sample[16]. The bulk density equation was followed:

Soil bulk density (g cm^{-3}) = oven-dry sample mass (g)/Sample volume (m^3) … (1)

SOC density was estimated with the following standard method of Han *et al.* (2010).

SOC density (kg C m^{-3}) = SDB (g cm^{-3}) *SOC (g C kg^{-1}) … (2)

The total SOC stock was determined by summing the mass of each sampled soil depth as follows[16]:

Soil carbon (Mg ha^{-1}) = SDB (g cm^{-3}) * soil depth interval (cm)* organic carbon (%) … (3)

Carbon sequestration rate (CSR) was estimated based on sediment rates (R) (global mean sedimentation rate in the mangrove forest = 2.8 mm per year[5], SDB and SOC[17].

CSR (g C m^{-2} $year^{-1}$) = SDB× SOC× R … (4)

Statistical analysis

One way analysis of variance (ANOVA) was used to compare various soil properties with depth, SBD, SOC and SOC stock across selected different age groups of mangrove areas. Prior to this analysis, normality in the data distribution and homogeneity of variance were evaluated. The SBD, SOC concentration and SOC stock ratios were analyzed using the Pearson r coefficient. All statistical analyses were performed using SPSS version 16.

Results and Discussion

The LAI was higher in the natural mangrove stands (Site-1) than in the restored areas and the values were 2.94-4.22 m^2 m^{-2}. The LAI values of 21 year, 17 year, 16 year, 15 year and 12 year-old stands (Site-2 to 6) were 2.66-3.48 m^2 m^{-2}, 1.81-2.89 m^2 m^{-2}, 1.56-2.2 m^2 m^{-2}, 1.97-2.41 m^2 m^{-2}, 1.79-2.41 m^2 m^{-2}, respectively. The average height of the mangroves in the natural stands was 20 feet, whereas in the restored mangrove it varied from 5 to 12 feet. The present study LAI data shows similar trend with the estimates of healthy riverine and dwarf mangroves of Mexican Pacific values of 4.66 and 2.39 m^2 m^{-2}, respectively[18]. The LAI values of the mangrove forests of Florida LAI ranges between 5.7[19] and 2.7 m^2 m^{-2} [20].

Soil parameters measured in six different sampling stations at four different depths are given in Table 1. All soil samples had 100% of clay particles up to 90 cm and hence the soil in the Pichavaram mangroves can be classified as a clay soil. The pH values were consistently within the range between 6.8 and 7.4 in all the sites. Generally, top soils had a pH value between 7.0 and 7.3 and the values of the sub-surface soil (30 cm and up to 90 cm) were between 6.8 and 6.9. Measurements of soil salinity showed that the interstitial salinity at natural as well in restored mangrove stands (Table1) was generally higher. The salinity of the surface horizon was higher than that of deeper horizons. The comparing results revealed that the restored mangrove area had higher degrees of salinity compared to natural mangrove

Table 1 — Soil parameters in Pichavaram mangroves.

Parameters	Restored mangrove stands	Natural mangrove stands
Soil texture	Clay soil	Clay soil
pH	7.07±0.17	7.12±0.09
Salinity (ppt)	11.43±1.99	10.99±1.64
Nitrite	0.63±0.47	0.78±0.14
Nitrate	17.33±6.57	32.55±4.97
Total phosphorus (P)	1057.55±287	1427.77±262

stands. Nutrient analysis, expressed in mg/kg, is given in Table 1. In restored areas, where young plants are growing, nutrients were relatively low and fairly constant with depth. At natural mangrove area, the nutrient levels were reasonably high, which indicates a deeper rooting zone, coinciding with the greater above ground biomass. Total phosphorus levels in the soils decreased with increase in depth. Nitrate and nitrite concentration increased with increase in depth.

Bulk density, an indicator of soil compaction, ranged widely throughout the sampled sites within different depth intervals[21,22]. The SBD shows increasing (natural stand) and decreasing trend with depth in all the sampled sites (Table 2). The mean of bulk density was highly significant between the sites. The top soil (0-15 cm) of the natural mangrove stand had lower bulk density (0.55± 0.01 g cm^{-3}) than restored mangrove stands (0.87 ± 0.01 g cm^{-3}) (p<0.01) (Table 3). The mean of bulk density between soil depth intervals was not significant (p=.065). Mangrove restored site (Site-5) showed the highest bulk density and it ranged from 1.13, 1.45, 1.37 and 1.35g cm^{-3} in various soil depth intervals of 0-15, 15-30, 30-60 and 60-90 cm, respectively (Fig. 2a). This higher bulk density is an indicator of low soil porosity and soil compaction. The high fine clay content of these soils and the correspondingly higher bulk densities, results in decreased soil permeability. By comparing restored and natural mangrove area, it was observed that soil in the natural mangrove has less bulk density as compared to restored mangrove area, because the permeability was slightly higher in the natural mangrove stands. Higher bulk density decreased the volume of macropores, leading to reduction in gaseous exchanges and also *vice–versa*. The natural mangrove area containing less bulk density leads to more gas exchange process.

Mangroves have high rates of sedimentation that promote the accumulation of organic compounds in soils through production of aerial and underground biomass[4,23]. In the present study, the soil organic carbon content was high in the natural mangrove area when compared to areas where the mangroves were restored. The mean SOC content in the top 90 cm of the natural mangrove stands (Site-1) varied from 25.8 to 34.3 (g C kg^{-1}), whereas it varied from 8.16 to 23.52 (g C kg^{-1}) in the mangrove planted areas (Fig. 2b).

The SOC content in the soil was significant with soil depth interval (p<0.003) and between sites (p<0.001). The SOC content in all the six sites were relatively quite similar (4.8-36.2g C kg^{-1}) (0-90 cm) to the global median SOC content of mangroves (22g C kg^{-1} [24]), which was also similar to the average estimated for the Zambezi River Delta (18g C kg^{-1}) and Madagascar (34g C kg^{-1})[25]. In contrast, some recent studies revealed that the mangroves soil C

Table 2 — The average soil bulk density, SOC content and SOC stock in the six different age groups of mangrove stands.

Parameters	Soil depth (cm)	Site-1	Site-2	Site-3	Site-4	Site-5	Site-6
Bulk density (g cm^{-3})	0-15	0.51	0.47	0.67	0.57	1.13	0.76
	15-30	0.56	0.62	0.83	0.74	1.45	0.98
	30-60	0.51	0.75	0.74	0.79	1.37	0.86
	60-90	0.66	0.67	0.61	1.08	1.35	0.68
SOC (g C kg^{-1})	0-15	29.5	36.2	27.8	21.5	11.1	21
	15-30	24.3	23.2	12.6	10.9	9.2	15.6
	30-60	34.3	9.8	9.6	4.8	7.1	9.5
	60-90	25.8	15	15.7	4.8	6.8	6.6
SOC stock (Mg C ha^{-1})	0-15	22.13	25.52	27.93	18.38	18.81	23.94
	15-30	20.41	21.57	15.68	12.10	20.01	22.93
	30-60	52.48	22.05	21.31	11.38	29.18	24.51
	60-90	51.08	30.15	28.26	15.55	27.54	13.46

Table 3 — Analysis of variance (ANOVA) tested for soil carbon parameters presented *p* and *f* values of sampling site and soil depth.

Parameters	Terms	df	f values	*p* values	Significance
Bulk Density	Soil depth	3	2.979	.065	NS
	Site	5	21.724	.000	**
SOC content	Soil depth	3	7.449	.003	*
	Site	5	8.447	.001	*
SOC stock	Soil depth	3	1.529	.248	NS
	Site	5	3.161	.038	NS

(p<0.005*; p<0.01**) **Significant 99%, NS- not significant concentrations ranged from 90 g C kg^{-1} to 260 g C kg^{-1}[26]. This global average SOC content may be rational in the context of conservative forests, assuming that C continues to increase with forest age. Corresponding with the other counties, the average SOC content in the present study (8.5–28.7 g C kg^{-1}) was lower than that of mangrove forests in Australia (10.0–73.0 g C kg^{-1})[27], Thailand (18.4–73.5 g C kg^{-1})[28], Brazil (10.9–214.2 g C kg^{-1})[29], Micronesia (73.0–215.0 g C kg^{-1})[30], and Saudi Arabian Red Sea coast (28.1–29.3 g C kg^{-1})[31]. On the other hand, SOC content in the present study was higher than that of reported values in Egypt (11.4–20.0 g C kg^{-1})[32], China (4.9–16.4 g C kg^{-1})[33], Japan (7.7–20.1 g C kg^{-1})[34], India (5.1–6.5 g C kg^{-1})[35], and Vietnam (7.8 g C kg^{-1})[36]. The organic carbon in this study was high in the top and mid layer of the soil. The increasing darkness of soil which was observed in the present study with depth was probably a reflection of the high organic carbon content. Based on the results, it can be concluded that rich organic matter was found more in natural mangrove areas than in restored areas and also the surface layer was rich in organic carbon and it decreased with increase in depth.

The amount of SOC sequestered in a 90 cm deep soil layer of natural and mangrove restored stands is given in Figure 2c. The SOC storage depends on different age groups of mangrove stands as a consequence of various soil properties, freshwater inflow, tidal flushing and different species composition. Overall, there was significantly lower SOC stock in the landward sparse mangrove zone (16 year-old stand) than in the high intertidal seaward zone (15, 17 year old stands) and dense mangrove area (21, 12 years old and natural stands). The SOC stock was higher for the natural mangrove stands in the dense mangrove area than that for the dense mangrove area in the intertidal marine mangrove zone, although there was no statistically significant difference for the SOC stock with site (p=0.038) and soil interval depth (p=0.248). In this study area, the SOC stock of the upper (0–90 cm) soil layer of the natural mangrove stands, 21year, 17 year, 16 year, 15 year and 12 year-old stands were 146.1 (Mg C ha^{-1}), 99.29 (Mg C ha^{-1}), 93.18 (Mg C ha^{-1}), 57.41 (Mg C ha^{-1}), 95.54 (Mg C ha^{-1}) and 84.84 (Mg C ha^{-1}), respectively (Fig. 3). In the Pearson correlation study, SOC content (r = -0.672) and SOC stock (r = -0.537) were significantly correlated to bulk density and SOC content respectively (Table 4), whereas SOC stock (r = –0.175) had negative correlation with bulk density.

Average SOC stock in the present study (57.41–146.1 Mg C ha^{-1}) was higher than that of mangrove

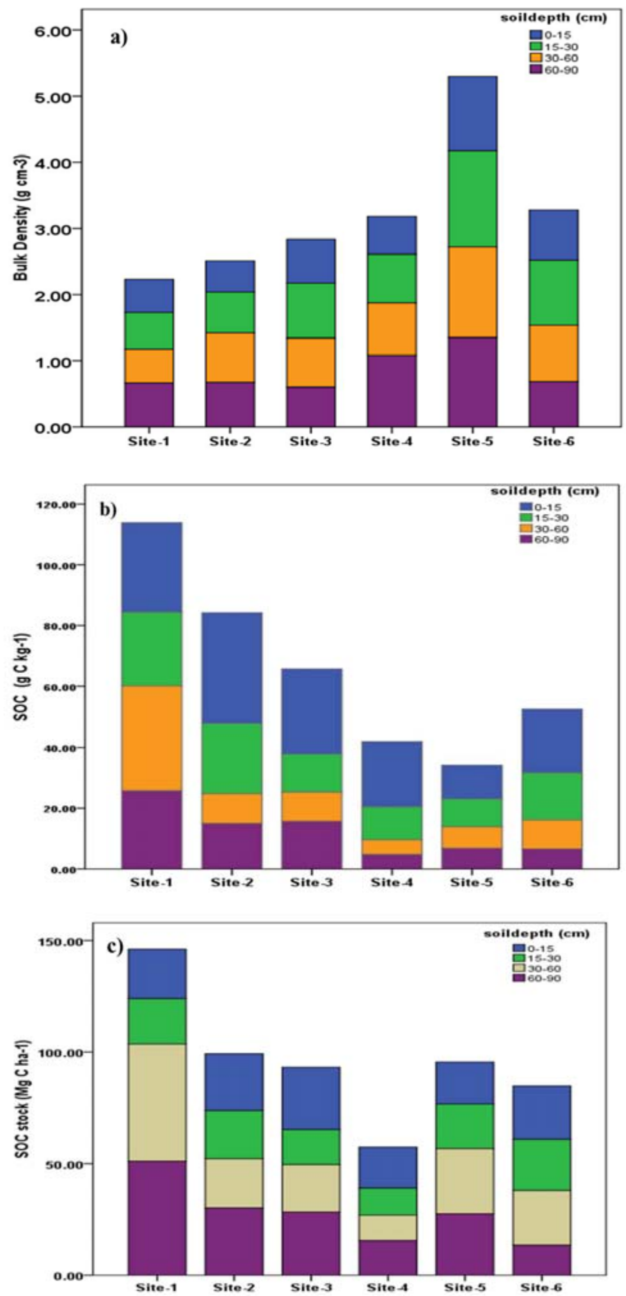

Fig. 2 — Distribution of a) Soil bulk density, b) SOC content and c) SOC stock from natural and restored mangrove stands with soil depth interval from Pichavaram mangroves.

Table 4 — The correlation matrix (Pearson (n)):

	Bulk density	SOC content	SOC stock
Bulk density	1		
SOC content	**-.672****	1	
SOC stock	-.175	**.537****	1

**Correlation is significant at the 0.01 level (1-tailed).

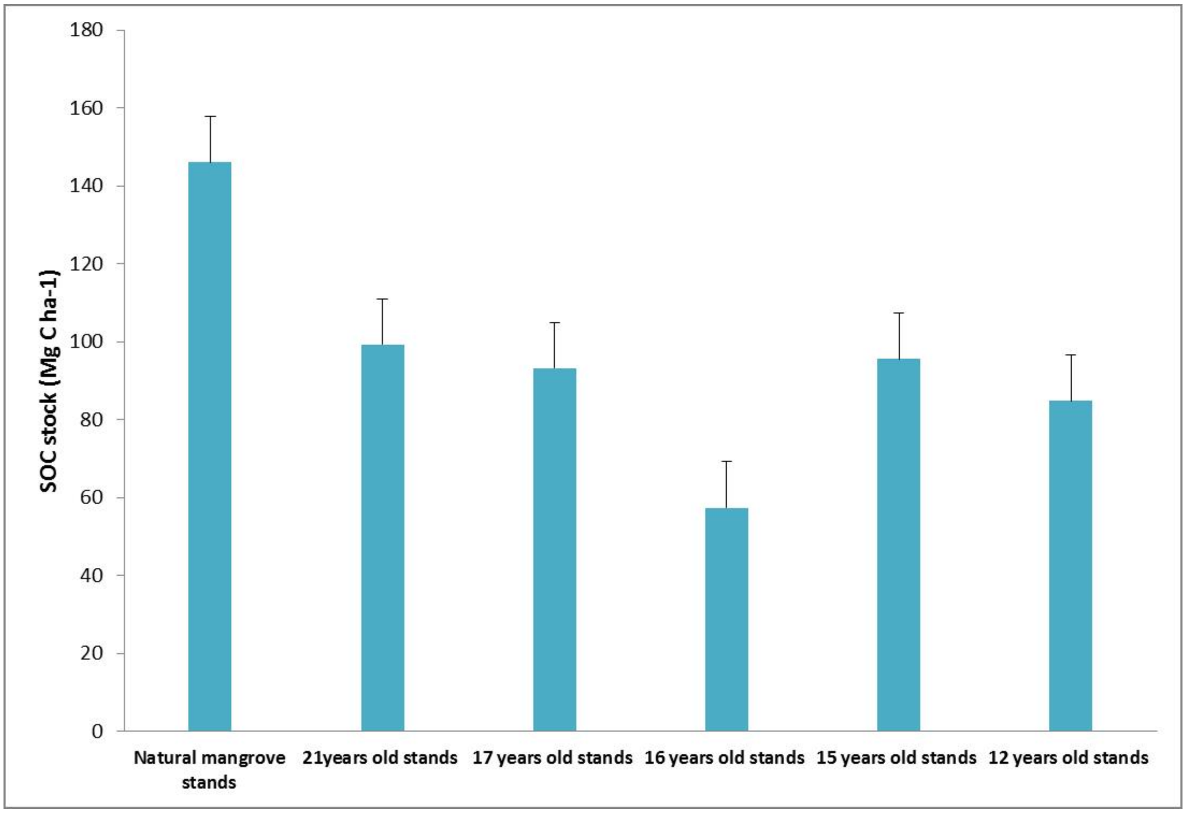

Fig. 3 — SOC stock from natural and restored mangrove stands from Pichavaram mangroves.

forests in Orissa, India. The average upper 30 cm depth of the sediment of natural stands had mean SOC of 54.3 ± 7.4 t C ha^{-1}, whereas plantations had 60.9 ± 13.9 (t C ha^{-1})[14]. In French Guiana, soil carbon stock reached more than 100 Mg C ha^{-1} in the senescent stage[37]. Soil carbon storage in the mature *Avicennia marina* forest in China was almost 200 (Mg C ha^{-1})[38], while it ranged from 546 Mg C ha^{-1} to 1084 Mg C ha^{-1} from the country of Dominican Republic[26] . The higher values were due to vegetation type and age of the mangrove stands. The SOC pool in the present study may be low because it was only based on data from the upper 90 cm soil layer. The carbon sequestration rate (CSR) of the natural stands (4.44 g C m^{-2} $year^{-1}$) was insignificantly higher than that of 21year, 17 year, 16 year, 15 year and 12 year-old restored stands. The values of these stands were 3.70 (g C m^{-2} $year^{-1}$), 3.27 (g C m^{-2} $year^{-1}$), 2.33 (g C m^{-2} $year^{-1}$), 3.17 (g C m^{-2} $year^{-1}$) and 3.02 (g C m^{-2} $year^{-1}$), respectively. In the present study, CSR of mangrove forests ranged from 2.33 to 4.44 g C m^{-2} $year^{-1}$. This estimation was lower than the previous estimated range of 37.0–205.0 g C m^{-2} $year^{-1}$ for mangrove soils in China[33], 150.0 g C m^{-2} $year^{-1}$ in Malaysia[39], 353.0 g C m^{-2} $year^{-1}$ in Australia[29], 2.0 to 6.1 g C m^{-2} $year^{-1}$ in Egypt mangrove soils, and 11.7–12.0 g C m^{-2} $year^{-1}$ in Saudi Arabian Red Sea coast mangrove soil[31]. The regional variations in SOC pools of mangrove forests could be related to a number of factors such as latitude, climate, geomorphology, edaphic condition, tides and the presence of different mangrove species. Further studies are needed to account for SOC in the total depth up to move than 200 cm of sediment deposits[40].

Conclusion

Carbon stock from the natural and restored mangrove forest at Pichavaram revealed that the mangroves have high potential for carbon sequestration. Based on the results, it can be concluded that high soil organic carbon stock and higher burial rates were found in natural mangrove areas than in restored areas. Similarly, the surface layer rich in organic carbon content decreased with increase in depth. The results suggest that the conservation of intact mangroves is more important than either natural or restored mangroves. But, the mangrove cover in India has come down from 6000 sq. km during 1960s to 4740 sq. km during 2015. In this regard, restoration and rehabilitation work is still required to improve the vegetation cover to derive not only the important ecosystem services of the mangroves but also to mitigate the impact of climate change. In the conservation and restoration efforts, the local community and government department should be involved like the MSSRF model of JMM.

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References

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

2 Dittmar, T., Hertkorn, N., Kattner, G & Lara, R.J., Mangroves, a major source of dissolved organic carbon to the oceans. *Glob. Biogeochem. Cycles.,* 20 (2006) GB1012.

3 Komiyama, A., Ong J.E & Poungparn, S., Allometry, biomass, and productivity of mangrove forests: a review. *Aquat. Bot.,* 89 (2008) 128–137.

4 Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M & Kanninen, M., Mangroves among the most carbon-rich forests in the tropics. *Nat. Geosci.,* 4 (2011) 293–297.

5 Breithaupt, J.L., Smoak, J.M., Smith, T.J., Sanders, C.J & Hoare. A., Organic carbon burial rates in mangrove sediments: strengthening the global budget. *Glob. Biogeochem. Cycles.,* 26 (2012) GB3011.

6 Alongi, D.M., Carbon sequestration in mangrove forests. *Car. Manag.,* 3 (2012) 313–322.

7 Selvam, V., Ravichandaran, K.K., Karunakaran, V.M., Mani, K.G., Beula, E.J & Gnanappazham L., Pichavaram mangrove wetlands: Situation Analysis, Chennai, 2010 pp, 39.

8 Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J & Duke, N., Status and distribution of mangrove forests of the world using earth observation satellite data, *Glo. Eco. . Biogeo.,* 20 (2011) 154–159.

9 Lovelock, C.E., Cahoon, D.R., Friess, D.A., Guntenspergen, G.R., Krauss, K.W., Reef, R & Saintilan, N., The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nat.,* 526 (2015) 559–563.

10 Rahman, A., Dragoni, D & El-Masri, B., Response of the Sundarbans coastline to sea level rise and decreased sediment flow: a remote sensing assessment. *Remo. Sens. Environ.,* 115(3) (2011) 121–3128.

11 Rivera-Monroy, V.H., Twilley, R.R., Davis III, S.E., et al., The role of the Everglades mangrove ecotone region (EMER) in regulating nutrient cycling and wetland productivity in South Florida. *Crit. Rev. Env. Sci. Tec.,* 41 (2011) 663-669.

12 FSI, India State of Forest Report 2013, *Forest Survey of India*, Dehradun, (2013).

13 FSI, India State of Forest Report 2015, *Forest Survey of India*, Dehradun, (2015).

14 Sahu, S.C., Kumar, M & Ravindranath, N.H., Carbon stocks in natural and planted mangrove forests of Mahanadi Mangrove Wetland, East Coast of India. *Curr. Sci.,* 110 (12) (2016) 25.

15 Selvam, V., Environmental classification on mangrove wetlands of India. *Curr. Sci.,* 84 (6) (2003) 757–765.

16 Kauffman, J.B & Donato, D., Protocols for the Measurement, Monitoring and Reporting of Structure, Biomass and Carbon Stocks in Mangrove Forests; Working Paper 86; CIFOR: Bogor, Indonesia, 2012, pp. 40.

17 Xiaonan, D., Xiaoke, W., Lu, F & Zhiyun, O., Primary evaluation of carbon sequestration potential of wetlands in China. *Acta. Ecol. Sinica.,* 28 (2008) 463–469.

18 Kovacs, J.M.J., King, M.L., Flores de Santiago, F. Flores-Verdugo. F., Evaluating the condition of a mangrove forest of the Mexican Pacific based on an estimated leaf area index mapping approach. *Environ. Monit. Assess.,* 157 (2009) 137–149.

19 Araujo, R.J., Jamarillo, J.C & Snedaker, S.C., LAI and leaf size differences in two red mangrove forest types in South Florida. *Bull. M. Sci.,* 60 (1997) 643–647.

20 Ramsey, E & Jensen, J.R., Remote sensing of mangrove wetlands: Relating canopy spectra to site specific data. *Photogram. Eng, Remo. Sens.,* 62 (1996) 939–948.

21 Howard, P.J.A., Loveland, P.J., Bradley, R.I., Dry, F.T., Howard, D.M and Howard, D.C., The carbon content of soil and its geographical-distribution in Great-Britain. *Soil. Use. Manage.,* 11(1995) 9–15.

22 Drewry, J.J., Cameron, K.C & Buchan, G.D., Pasture yield and soil physical property responses to soil compaction from treading and grazing -a review. *Aust. J. Soil. Res.,* 46 (2008) 237–256.

23 Adame, M.F., Kauffman, J.B., Medina, I., Gamboa, J.N., Torres, O., Caamal, J.P., Reza, M., & Herrera-Silveira, J.A., Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean, *PLoS One*., 8(2) (2013) e56569.

24 Kristensen, E., Bouillon, S., Dittmar, T & Marchand, C., Organic carbon dynamics in mangrove ecosystems: a review. *Aquat. Bot.,* 89 (2008) 201–219.

25 Jones, T.G., Ratsimba, H.R., Ravaoarinorotsihoarana, L., Cripps, G and Bey, A., Ecological variability and carbon stock estimates of mangrove ecosystems in Northwestern Madagascar. *Forests.,* 5 (2014) 177–205.

26 Kauffman, J.B., Heidre, C., Norfolk, J & Payton, F., Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. *Ecol. Appli.,* 24 (2014) 518–527.

27 Alongi, D.M, Clough, B.F, Dixon, P & Tirendi F., Nutrient partitioning and storage in arid-zone forests of the mangroves *Rhizophora stylosa* and *Avicennia marina, Trees.,* 17 (2003) 51–60.

28 Alongi, D.M., Trott, L.A., Wattayakorn, G & Clough, B.F., Below- ground nitrogen cycling in relation to net canopy production in mangrove forests of southern Thailand, *Mar. Biol.,* 140 (2002) 855–864.

29 Sanders, C.J., Smoak, J.M., Naidu, A.S., Sanders, L.M., Patchineelam, S.R., Organic carbon burial in a mangrove forest, margin and intertidal mud flat. *Estuar. Coast. Shelf Sci.,* 90 (3) (2010) 168–172.

30 Kauffman, J.B., Heider, C., Cole, T., Dwire, K.A., Donato, D.C., Ecosystem C pools of Micronesian mangrove forests: implications of land use and climate change. Wetlands., 31 (2011) 343-352.
31 Eid, E.M., El-Bebany, A.F & Alrumman, S.A., Distribution of soil organic carbon in the mangrove forests along the southern Saudi Arabian Red Sea coast, *Rend. Fis. Acc. Lincei.,* 27 (2016) 629–637.
32 Eid, E.M & Shaltout, K.H., Distribution of soil organic carbon in the mangrove *Avicennia marina* (Forssk.) Vierh. along the Egyptian Red Sea coast, *Reg. Stud. Mar. Sci.,* 3 (2016) 76–82.
33 Yang, J., Gao, J., Liu, B & Zhang, W., Sediment deposits and organic carbon sequestration along mangrove coasts of the Leizhou Peninsula, southern China, *Estuar. Coast. Shelf. Sci.,* 136 (2014) 3–10.
34 Khan, M.N.I., Suwa, R & Hagihara, A., Carbon and nitrogen pools in a mangrove stand of Kandeliaobovata (S., L.) Yong: vertical distribution in the soil vegetation system. *Wet. Ecol. Manag,* 15 (2007) 141-153.
35 Ray. R., Ganguly, D., Chowdhury, C., Dey, M., Das, S., Dutta, M.K., Mandal, S.K., Majumdar, N., De, T.K., Mukhopadhyay, S.K & Jana, T.K., Carbon sequestration and annual increase of carbon stock in a mangrove forest, *Atmos. Environ.,* 45 (2011) 5016–5024.
36 Tue, N.T., Ngoc, N.T., Quy, T.D., Hamaoka, H., Nhuan, M.T & Omori, K., A cross- system analysis of sedimentary organic carbon in the mangrove ecosystems of XuanThuy National Park, Vietnam, *J. Sea Res.*, 67 (2012) 69–76.
37 Marchand, C., Soil carbon stocks and burial rates along a mangrove forest chronosequence (French Guiana). *For. Ecol. Manag.,* 384 (2017) 92–99.
38 Wang, G., Guan, D., Peart, M.R., Chen, Y & Peng, Y., Ecosystem carbon stocks of mangrove forest in Yingluo Bay, Guangdong Province of South China, *Forest. Ecol. Manag.,* 310 (2013) 539–546.
39 Eong, O.J., Mangroves -a carbon source and sink. *Chemosph.,* 27 (1993) 1097–1107.
40 Ren, H., Chen, H., Li, Z.A & Han, W., Biomass accumulation and carbon storage of four different aged *Sonneratia apetala* plantations in Southern China, *Plant. Soil.,* 327 (2010) 279–291.