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Assessment of Blue Carbon Stock of Coringa Mangroves: Climate Change Perspective

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Abstract: 'Blue carbon' has recently seized the attention of the scientific communities as they are believed to provide the benefits of climate change mitigation given its high potential to store carbon under unfavourable conditions. Keeping in mind the importance of the carbon storage capacity of mangroves, the present study has been carried out to determine the sedimentary organic carbon stock in Coringa mangroves. The value of total organic carbon (TOC) ranges from 0.63 to 2.76% with a mean value of 1.30±4.3%. The value of total nitrogen (TN) varies from 0.04 to 0.19% with an average value of 0.08±0.03%. Dry Bulk Density (DBD) ranges from 0.63 to 2.58 gm cm^{-3} with a mean value of 1.33±0.19 gm cm^{-3}. The mean value of sedimentary carbon stock (SCS) in Coringa mangrove is 158±32.60 Mg C ha^{-1}. This amounts to the below-ground sedimentary carbon stock being 1.86 Tg C and represents the equivalent CO_2 emission of 579.9 Mg CO_2e ha^{-1}. The TOC, TN, DBD, and SCS show significant spatial variation among the different sites. The maximum carbon stock is found in densely vegetated Coringa mangroves, followed by moderately vegetated Gaderu mangroves and the least is found in the degraded forest of Matlapalem mangroves. Grain size parameters signify that there is no definite relationship between the organic carbon content and the abundance of finer sediments fractions in the Coringa mangrove. The higher carbon stock in Coringa mangroves reveals their importance in storing carbon and hence could have relevance on a national scale too and play an important role in climate change mitigation

Keywords: Mangroves; Organic carbon content; Total nitrogen; Organic carbon stock; Grain size.

Blue Carbon Footprints

"Carbon sequestration" is the process of storage of carbon either deliberately or through natural processes. It consists of the removal or diversion of carbon dioxide from sources and stored in the ocean, geologic, and terrestrial (soil, sediments, and vegetation) environments. Before anthropogenic emission of CO_2 began, the natural processes maintained a near balance between the uptake and release of CO_2 but an increase in human activities like fossil fuel combustion (coal, gas, and oil) led to a substantial increase in carbon dioxide. The atmospheric CO_2 increased from 280 to 380 ppm over the last 250 years contributing to global warming (Giri et al., 2008). With this continuous increase of carbon in the atmosphere, natural CO_2 uptake mechanisms become insufficient to offset the continuously increasing emission of anthropogenic carbon. This disbalances the natural carbon cycle. Several coastal ecosystems have significant potential to store carbon which include tidal marshes, seagrasses, mangroves, swamps, etc.

The area occupied by these coastal ecosystems is < 5% of the total earth's surface but plays a crucial role in controlling the carbon cycle on a global level (Twilley et al., 1992). Despite occupying only 0.5% of the

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global coastline, the mangrove ecosystem contributed around 10-15% of carbon storage in sediments globally (Jennerjahn & Ittekkot, 2002). Carbon stored in mangrove plant parts like leaves, stems, wood, etc. are called above-ground carbon stock and is stored for a short period. Carbon is also stored in existing biomass like bacteria, animals, plants, and fungi, and it also occurs in a dissolved form which is stored in surface water and groundwater (Wylynko, 1999). Mangrove sediments are known to store a large amount of carbon for a longer period which is known as below ground carbon stock. This huge carbon storage in mangrove sediments are due to the multifaceted and intricate root structures, high rates of sedimentation, waterlogged soil condition which is free from fire risks, and anoxic soil condition which results in carbon burial rates that is an order of magnitude greater and carbon turnover rates about a thousand times lesser compared to the terrestrial forests (Alongi, 2012; McLeod et al., 2011). The capability of mangrove ecosystems to store large amounts of soil carbon (around 5–10.4 Pg globally) (Duarte et al., 2013; Jardine & Siikamäki, 2014) for a longer time (of about a millennium) makes these ecosystems an important sink of carbon and helps in minimising greenhouse gas (GHG) emissions. Hence conserving mangrove forests are a low-cost option for the mitigation of climate change (Murdiyarso et al., 2015; Siikamäki et al., 2012). Moreover, it is difficult to determine whether any particular coastal ecosystem's wetland or mangrove swamps act as a net source or sink of carbon. This is because on one hand these ecosystems are known to have a great potential to store carbon (CO_2) in their sediments, soils, and plant parts, on the other hand, they emit carbon in the form of methane (CH_4) gas. But this sink and source capacity depends upon the geomorphology, biogeochemical processes, hydrology, and hydrodynamic conditions. Hence, more research is required to evaluate the role of mangroves as the sink or sources over time and their role in mitigating climate change and international trading of carbon.

Blue carbon stock in mangroves gives an idea about 'how much carbon is present in the soil' and hence represents the amount of carbon that is susceptible to be emitted as carbon dioxide upon removal of mangroves. Therefore, carbon stock determination in mangroves reveals how much avoiding mangrove degradation can lead to a reduction in carbon dioxide emissions. The assessment of carbon stock provides a quantitative measure of the sensitivity and vulnerability of mangrove ecosystems to climate change. It is important to estimate the spatial distribution of carbon stocks in mangroves to recognise the role of specific sites in carbon repositories and hence in climate change mitigation. This also helps in conserving mangroves where conservation drive could be the focus on the sites having high potential to store carbon. In Indian mangroves, several studies on ecosystem carbons stock have focussed on the biomass carbon stock (both above ground and below ground) as well as carbon stock in sediments across Thalasseri Wetland in Kerala, Bhitarkanika and Mahanadi mangroves, Sundarbans mangroves, Pichavaram mangroves, etc. (Banerjee et al., 2020; Bhomia et al., 2016; Gnanamoorthy et al., 2019a; Harishma et al., 2020; Mizanur Rahman et al., 2015; Ranjan et al., 2011; Ray et al., 2011; Sahu et al., 2015; Vinod et al., 2019). The sedimentary carbon pool in different land use types covering planted (92±20 Mg C ha^{-1}), dense (134±17 Mg C ha^{-1}), sparse mangroves (177±14 Mg C ha^{-1}), and abandoned aquaculture pond (61±8 Mg C ha^{-1}) has been checked by Bhomia et al. (2016) in Bhitarkanika mangroves, Odisha, India. Their study indicates that planted mangroves also has the potential to store carbon in significant amount showing the importance of mangrove plantation and restoration in carbon storage. The role of the Indian part of Sundarbans mangroves has been identified by Ray & Jana (2017) as a potential coastal habitat to sequester and store anthropogenic carbon dioxide emitted from the proximate cold based thermal power plant in Kolaghat (which is located around 100 km from the mangrove) between late December 2011 and early January 2012. They found that Sundarbans mangrove sequester carbon dioxide (2.79 Tg C) almost at the same rate as the carbon dioxide emission from a Kolaghat thermal power plant (2.83 Tg C). Similarly, a study by Nam et al. (2016) assessed the capacity of restored mangrove forests in Vietnam to store and sequester carbon in artificially and naturally regenerated mangrove coastal ecosystems. They found that the mean total ecosystem carbon stock in the planted mangroves of the Can Jio Mangrove Reserve Forest is around 889±111 Mg C ha^{-1} and that of naturally regenerated forests of The Kien Vang Protection Forest is 884±58 Mg C ha^{-1} suggesting that even after 35 years, both naturally and anthropogenically restored mangroves appear to store a similar amount of carbon in their soil, concluding that conservation and protection of mangroves are equally important for carbon storage. Looking at the incredible carbon storage capacity of mangroves, sedimentary carbon stock assessment becomes very relevant for the assessment of total ecosystem carbon stocks. The long-term carbon burial also depends on the sedimentary carbon stock of mangroves (Kristensen et al., 2008). Keeping in mind the role of mangroves in storing carbon, this study aims to see the amount of carbon stored in mangrove sediments (i.e., carbon stock), their spatial variation in different environmental settings, and the role of textural on the sedimentary carbon distribution.

Material and Methods

Study Area

The Coringa mangroves are located at 16°32′N-16°55′N and 82°11′E-82°21′E in the East Godavari District and are considered to be the second-largest mangrove ecosystem (187.8 sq. km) in the Indian subcontinent (FSI, 2021). It is a river-dominated mangrove and is nourished by the Godavari River, which is sub-divided into two distributaries, of which the major branch is the Gautami-Godavari and the other is the minor branch known as the Vasishta-Godavari at the township of Dowaleswaram which is considered to be the head of the delta. Along with organic and inorganic material fluxes from the mangrove system, a huge amount of city sewage (through various canals) also enters the Kakinada Bay from Kakinada township (Shaik et al., 2015). Coringa mangroves are exposed to extensive human impingement due to agricultural practices (paddy), industrial fertilisers (factories), port expansions, etc. Moreover, anthropogenic activities, for example, mangrove denudation like coastal aquaculture have now become a serious problem in Coringa (Satyanarayana et al., 2002).

The present study was carried out in the Gautami Godavari branch. The Gautami Godavari estuary further sub-branches into various creeks and canals to sustain dense mangrove vegetation, famous as the Coringa mangrove forest. These creeks get finally joined to the Kakinada Bay, a shallow bay, covering approximately 150 km^2 area and opening into the Bay of Bengal. Coringa creek (26 km) and the Gaderu creek (11 km), are the primary and most significant creeks within the Coringa mangrove forest, joining the estuary proper at one end and the Kakinada Bay on the other (Figure 1). Other creeks i.e., Matlapalem also feed the mangrove areas before ending in the Kakinada Bay.

Field Sampling and Measurements

Two sampling campaigns were conducted in March 2018 and March 2019 along with the Gautami-Godavari mangrove complex. Sampling was carried out across the entire stretch of the Coringa mangrove complex from the sites covering the various environmental settings like dense forest, degraded mangrove sites, natural/pristine, anthropogenically disturbed areas representing different land use and land cover patterns of the mangroves as this influence the carbon dynamics. Seaward tidal influence and geomorphic settings were also considered while choosing the sampling locations as they appear to be largely driven by environmental settings and conditions, mainly hydrodynamics, vegetation condition, and landforms (Kusumaningtyas et al., 2019). Core M1 was taken from Matlapalem mangrove creek which represents a degraded and deforested site. Two cores (C1 and C2) were taken from densely vegetated Coringa mangrove forests. Coringa forests are difficult to access and hence are secluded from human intervention and have a high basal area which ranges from (2.1-10.9 m^2) (Satyanarayana et al., 2002) and represents dense forests. Gaderu mangroves have a low basal area (around <1.9 m^2) (Satyanarayana et al., 2002) which might be due to the degradation of old forests or poor regrowth of new ones (Satyanarayana et al., 2002) and hence represents the moderately vegetated forests. Three cores (Core G1, G2, and G3) were taken from Gaderu mangroves (representing different settings). The sub-setting of Core G1 suggests that it is taken from the southern part of the Gaderu region near the mouth of the Godavari estuary and close to the human dwellings. Core G2 is taken from the northern region of Gaderu creek which is near the mouth of Kakinada Bay. Core G3 was taken from the region close to the Bay of Bengal and represents relatively pristine mangroves due to difficult accessibility in that particular region (i.e., undisturbed with no anthropogenic influence). Hence Coringa mangrove represents dense mangrove forests, Gaderu represents moderately dense and Matlapalem represents highly degraded and sparse mangroves (as shown in Table 1). The other cores i.e., Core A1 were taken from the Coringa Extended Creek which receives direct effluents from aquacultural ponds and hence represents an anthropogenically disturbed creek. Core B1 was taken from Kakinada Bay close to the mangroves. Hence total of eight cores was collected to assess ecosystem carbon stock at different sites and different land use types representing the varying degree of disturbances as shown in Table 1. It is to be noted since Core A1 is taken from the creek receiving direct aquacultural ponds and Core B1 from Kakinada Bay, these two cores do not represent mangrove sites and so these two cores have been excluded while calculating carbon stock but have been used to see their biogeochemistry.

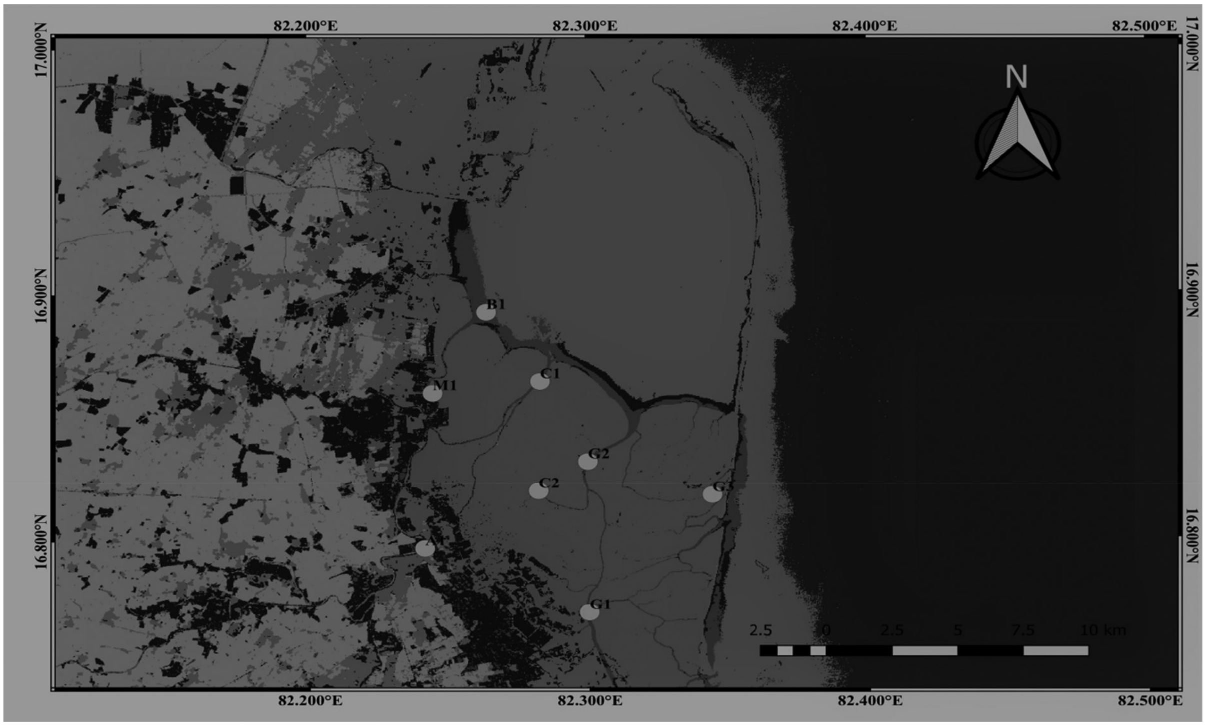


Figure 1: Study area map showing the sampling locations of the cores in the Coringa mangrove forest, Andhra Pradesh.

Table 1: Sampling locations based on land use type and disturbance pressure at each location within the Coringa mangroves complex (NA- Not Applicable)

Land Use Type	*Sampling Plots*	*Disturbance*	*Degradation Status*
Disturbed creek (due to aquaculture effluents)	A1	Very high	Heavily degraded
Kakinada Bay	B1	NA	NA
Matlapalem	M1	High	High degradation
Coringa	C1, C2	Low	Low degradation
Gaderu	G1, G2	Medium	Moderately
Gaderu	G3	Negligible	Intact

Analyses

The core sample was collected using steel corer of length 150 cm and the proper care was taken to extract the core without disturbing the sediment package. The collected core is sectioned into 2 cm intervals up to 20 cm, and then further sectioned into 5 cm intervals for the rest of the core. The depth of core samples is variable as it is not possible to cover the full sediment record, due to logistic problems like the complex nature of roots. The depth of the sediment cores used to estimate core carbon content ranged from (42 to 116 cm). The length of Core M1 (42 cm), Core C1 (102 cm), Core C2 (92 cm), Core G1 (80 cm), Core G2 (100 cm), Core G3 (116 cm), Core A1 (112 cm) and Core B1 (85 cm). To see the spatial variability of sedimentary organic carbon stock, we standardised the carbon stocks to 1m depth. For the sediment cores which have a depth of less than 1m, we extrapolated the C_{org} stocks to 1m depth.

Bulk Carbon Density

After carefully removing the noticeable roots and plant fragments, the samples were dried at 60°C for about 48-72 hours (to avoid oxidation of carbon) until it achieves a constant weight and ground to a fine powder. Some studies determined that it requires at least 48 hours for samples to attain a constant dry mass when dried at 60°C (Donato et al., 2012). Bulk density was determined for each interval by dividing the oven dried sample by total sample volume (MacKenzie et al., 2016) using the following equation:

$$\text{Soil bulk density } (g/cm^3) = \text{Oven-dry sample mass } (g) / \text{Sample Volume } (m^3)$$

Elemental Carbon Analysis

For concentrations of total carbon (TC) an aliquot of dried powder (10-30 mg for sediment samples) was taken in tin cups and analyzed on a Eurovector EA 3000 elemental analyzer. For C_{org}, samples, in the same amount as mentioned earlier, were taken in silver cups and acidified with 1N HCl, and subsequently dried at 40ºC for 24 hours or longer to remove the carbonates. Acetanilide Hekatech 302781 (C: 71.10% ± 0.23) was used as a standard to calibrate the instrument and Low soil standard OAS 310391(C: 1.61% ± 0.09) was used as a working standard to check the accuracy of the results after every five measurements. The accuracy of the methods measured by international standards was 0.017% and the precision of all the measurements was less than 1%.

Sedimentary Carbon Stock Calculation

Total soil carbon content is determined by summing the mass of each sampled soil depth. In this study, the total soil carbon pool was determined by measuring bulk density and percentage carbon content at each depth/ layer. The sedimentary carbon stock is determined by using the following equation (Nguyen et al., 2014):

Sedimentary carbon density

$$(C_{org} \text{ density, g/cm}^3) = \text{Bulk Density} * \text{TOC\%}$$

$$C_{org} \text{ stock (g/cm}^2) = C_{org} \text{ density (g/cm}^3) * \text{thickness interval (cm)}$$

The total sedimentary carbon stock from one core was summing up C_{org} stocks at all depth intervals from the entire core.

Step-Wise Carbon Stock Calculations

- Dry Bulk Density = Dry weight of sediment/ Volume of sediment (Ranjan et al., 2011)
- Sediment Carbon Stock = It can be calculated using following equation
- Amount of carbon in core section (g/cm^2) = SCD (g/cm^3) * thickness interval (cm)
- Core carbon content (g/cm^2) = ∑Amount carbon in each core section
- Total core carbon (MgC/ha) = Summed core carbon (g/cm^2) * (1Mg/1,000,000g) * (100,000,000 cm^2/ ha)
- Total sedimentary carbon stock (MgC) = Average core carbon (Mg C ha^{-1}) * Area (ha)

Grain Size

For grain size analysis, 1-3 gm of sediment were taken in a long test tube. Sediments were oxidised using 5-10 ml of 30% hydrogen peroxide (H_2O_2) in the test tube (add stepwise starting with 0.5 ml till effervescence ceases around 1.5 hours). Add 5ml of 1N HCl (hydrogen chloride) to remove inorganic carbon/or carbonates from the sediments. Excess HCl was evaporated by placing the long tubes containing samples in wide mouthed beaker half filled with water on the hot plate once it starts boiling for around 15-20 minutes. Add 0.3 gm of Calgon/or Tetrasodium pyrophosphate decahydrate ($Na_4P_2O_7.10H_2O$) to the sample and mix well. Leave to cool till 2 layers of formation occur. Remove the supernatant using a glass pipette and add 5 ml of water to the test tubes. Sonicate the samples in the sonicator having around 40 ml of water. The sample is ready to use for analysis in the Microtrac S3500 Laser diffraction particle size analyser, to avoid clumping of the fine grains and to achieve the unbiased detection of grain size.

Equivalent Carbon Dioxide Emission (CO_2 equivalent)

The CO_2 equivalent was determined by multiplying the carbon stock by 3.67, this is because one ton of carbon is equal to 3.67 tons of CO_2 which signifies an equal quantity of carbon lost from long-lived pools (Carnell et al., 2018; Siikamäki et al., 2013).

Statistical Analysis

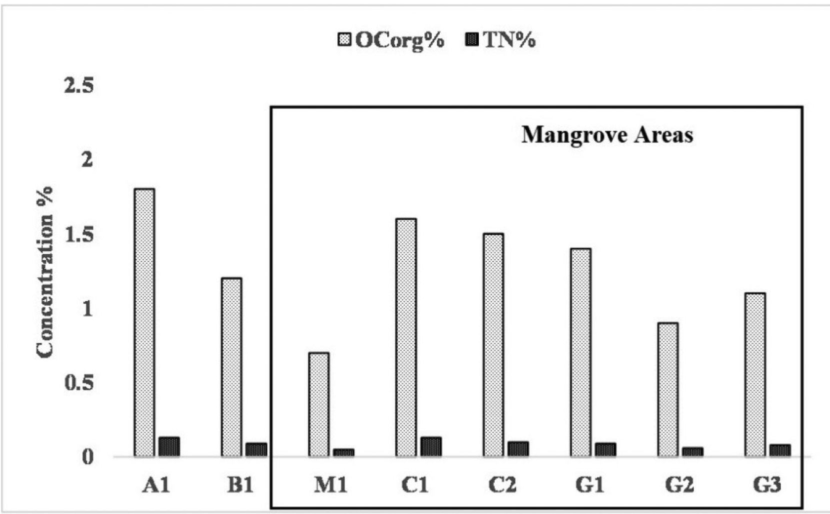
(a) *Analysis of Variance:* The observed dataset of sedimentary core carbon content (carbon stock) was subjected to a one-way analysis of variance (ANOVA) using Excel with a significance level of 0.05 and a confidence level of 95%.

(b) *Correlation Analysis:* To identify the possible relationship among different sediment fractions i.e., grain size (sand, silt, and clay) and sedimentary organic carbon contents, Pearson's correlation analysis was using IBM SPSS Statistics 21. The test results were testified with a confidence level of 99% and p values of 0.01.

Result and Discussion

Total Organic Carbon, Total Nitrogen Content Variability

The value of total organic carbon (TOC) in core sediments ranges from 0.63-2.76% with an average value of 1.30±0.43% while the values of total nitrogen (TN) vary from 0.04 to 0.19% with an average value of 0.08±0.03%. The highest organic carbon and total nitrogen content have been observed in creeks receiving direct aquaculture effluents (i.e., core A1) which may be due to its location just outside the aquacultural pond (as shown in Figure 2). This is due to high nutrient loading from aquacultural effluents which may result in the eutrophic conditions thereby positively affecting organic carbon content in anthropogenically impacted sediments (Bournazel et al., 2015). The upper few layers of Core A1 (i.e., 0 to 40 cm) have high carbon and nitrogen content which decreases down the core (Figure 3) indicating the influence of aquacultural effluents and domestic sewage in the upper few segments of the core (Prasad & Ramanathan, 2009). Among the mangrove



Sampling Points	Disturbances
A1= Aquaculture	Highly disturbed
M1= Matlapalem	Degraded
C1, C2= Coringa	Dense
G1, G2= Gaderu	Moderate
G3= Gaderu	Pristine

Figure 2: Spatial variation of total organic and total nitrogen content in the core sediments samples of Coringa mangrove complex.

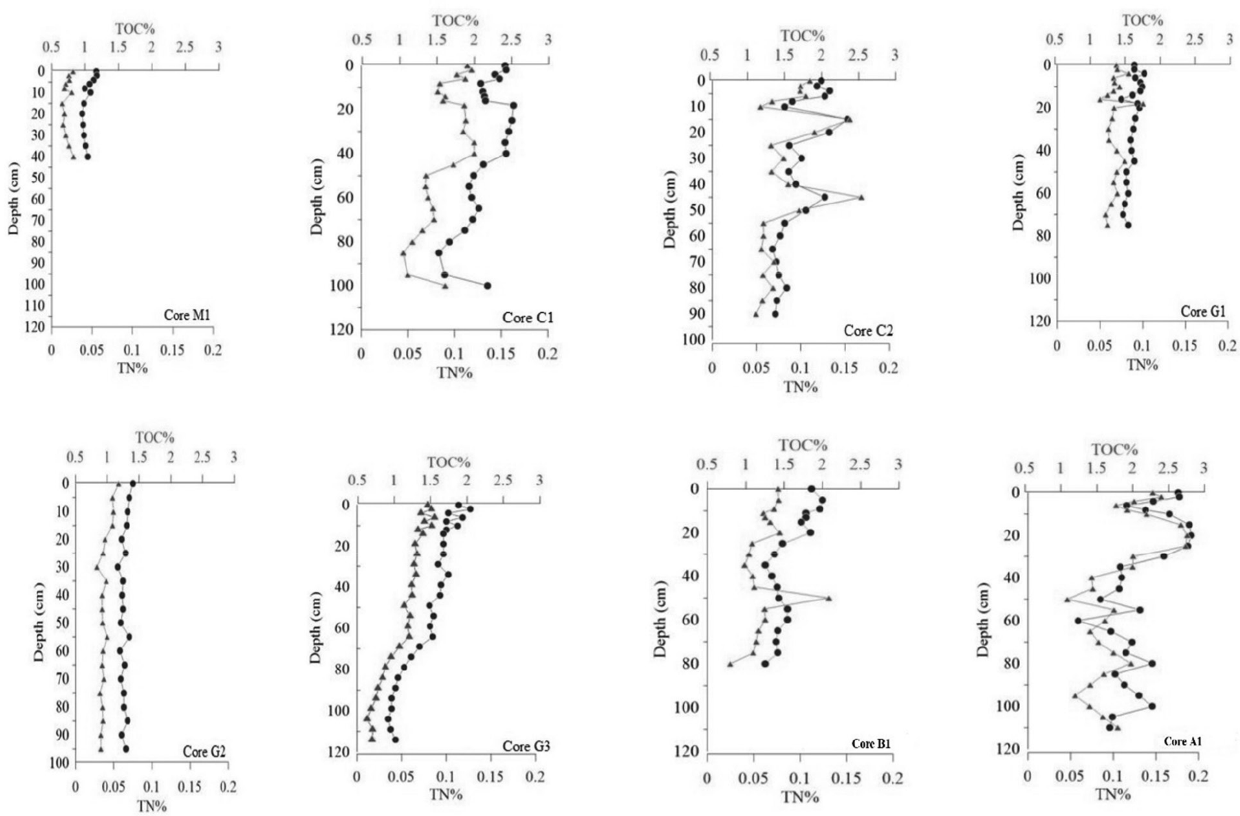


Figure 3: Downcore variations of sediment properties of TOC and TN at the studied sites (triangle represents TOC% and circle represents TN%).

region, the highest value of TOC and TN is found in dense and vegetated Coringa mangroves (C1 and C2) followed by the moderately dense Gaderu region (G1, G3, G2), and the lowest is found in Core M1 in degraded Matlapalem. The reason for the highest value in Coringa mangroves may be because the dense forest of Coringa mangroves has a dense root system and hence can hold the sediments effectively. This result is consistent with the previous study in the same region (Coringa mangroves) which also shows high TOC in the area closer to the dense vegetation (Bouillon et al., 2003). Organic carbon is lowest in Core M1 which is taken from the degraded and deforested sites. The low OC% in this area may be because of the lack of mangrove vegetations and roots which results in the transport and loss of organic carbon (Boone Kauffman et al., 2017; Pérez et al., 2017) and this suggests that degradation and deforestation activities affect the organic carbon content significantly. Samples from Kakinada Bay (KKD) (not far away from the mangrove region) show lower TOC and TN content than Coringa and Gaderu mangrove regions. This may be because the sample has been taken from the bay region which is unvegetated, has no mangroves, and have different soil conditions i.e., it has more sand percentage and very less clay (shown in the later section). The TOC and TN content of Kakinada Bay is more than the Matlapalem mangroves, this may be due to the Kakinada Bay which has the influence of domestic and agricultural wastes carried through the Godavari canal passing through the Kakinada township (Tripathy et al., 2005) which results in high nutrient concentration (carbon and nitrogen) in this region. Looking at the high nutrient profile of KKD bay than Matlapalem mangroves we can assume that it may supply the organic carbon to the Matlapalem mangroves during high tide conditions. Hence more study is required to correctly analyze this nutrient flux. The spatial variation is found to be significant for TOC ($p < 0.01$) and TN ($p < 0.05$) across the various region of the Coringa mangrove complex (Table 2).

The vertical variation of TOC and TN in different studied cores is presented in Figure 3. In all the cores TOC% is mostly enriched near the surface and its values decreased down the core as per the general trend the value of TOC and TN decreases with depth in all the cores except in Core G2 which does not show any trend down the core. A good correlation between TOC and TN contents has been observed in all the cores as depicted by Pearson correlation coefficient (r) values of >0.5 ($p<0.05$).

The organic carbon and nitrogen content of the present study has been compared with the other study of Indian mangroves as well as the mangroves all across the world (Table 3). The comparison reveals that the carbon and nitrogen content in the Coringa mangroves is consistent with the previous studies done on Indian mangroves. The value of TOC and TN in our study is similar to the Pichavaram and Bhitarkanika but less than that of Sundarbans mangrove in India and much less than all the mangroves worldwide. The probable reason for the spatial, regional, and global variation of organic carbon and total nitrogen between various mangroves in India as well as other mangroves worldwide might be due to the differences in multiple factors like mangrove cover and structure, mangrove stability, hydrodynamic, and geomorphology, anthropogenic activities, storm surges, mangrove productivity, grain size, and management activities, etc.

Dry Bulk Density Variation (DBD)

Dry Bulk Density is an indicator of soil compaction and ranged widely throughout the sampling sites (Drewry et al., 2008; Howard et al., 1995). In the present study, DBD ranges from 0.63 to 2.58 g cm^{-3} with an average value of 1.33±0.19 g cm^{-3} and shows significant variation spatially (p = 0.05) (Table 2). In this study, DBD follows the general trends and is maximum in areas having low organic carbon content i.e., in Core M1, and lowest in dense Coringa mangroves (Core C2). The lowest DBD in Coringa mangroves indicate that soil in this region is least prone to compaction which makes the soil more fertile. The increased fertility might increase the vegetation and hence soil carbon stock.

Table 2: Analysis of Variance (ANOVA) for different soil parameters in eight study locations of Coringa mangrove

Properties	*Value Range (Mean±SD)*	*ANOVA*
Total Organic Carbon (TOC)	0.63-2.76% (1.30±0.43%)	F_{stat}=28.2, F_{crit}=2.06 (p<0.01)
Total Nitrogen (TN)	0.04-0.19% (0.08±0.03%)	F_{stat}=33.65, F_{crit}=3.89 (p<0.05)
Dry Bulk Density (DBD)	0.63-2.58 (1.33±0.19) g cm^{-3}	F_{stat}=2.04, F_{crit}=2.06 (p=0.05)
Sedimentary Carbon Stock (SCS)	115-195 (158±34.6) Mg C ha^{-1}	F_{stat}=8.2, F_{crit}=2.28 (p<0.01)

Table 3: Comparison of organic carbon content and total nitrogen of core sediment samples of Coringa mangrove complex with different mangrove ecosystems across the world

Mangrove sites	*TOC%*	*TN%*	*References*
Coringa mangroves (1)	1.3±0.43	0.08±0.03%.	Present Study
Coringa mangrove (dry) (2)	1.43±0.64	0.11±0.06	Priya 2019
Coringa mangrove (wet) (2)	1.44±0.35	0.09±0.04	Priya 2019
Pichavaram mangrove (3)	1.2±0.52	0.08±0.03	(Ranjan et al., 2011)
Picahavaram (4)	1.3±1.2	0.1±0.1	Sappal, 2016
Pichavaram (5)	2.84±0.44 (restored)	0.00178 (restored)	(Gnanamoorthy, et al., 2019a)
Pichavaram (5)	1.39±0.82 (planted)	0.0033 (planted)	(Gnanamoorthy et al., 2019a)
Bhitarkanika mangrove (6)	1.20±0.19	0.09±0.03	(Bhomia et al., 2016)
Sundarbans, Bangladesh (7)	2.21±1.95	NA	(Akther et al., 2021)
Global studies (9)	5.70%	NA	(Jardine & Siikamäki, 2014)
Indonesia (10)	10.45%	NA	(Murdiyarso et al., 2015)
Montecristi, Dominican Republic (11)	~20%	NA	(Kauffman et al., 2014)
Ruunuw mangrove, Yap (12)	10.43±2.19	0.33±0.08	(Kauffman et al., 2011b)
Airai mangrove, Palau (12)	18.26±2.44	0.50±0.10	(Kauffman et al., 2011b)
Berau (13)	5.7±3.7	0.17±0.08	(Kusumaningtyas et al., 2019)
Eastern Segaran Anakan (13)	7.7±1.8	0.26±0.04	(Kusumaningtyas et al., 2019)
Central Segara Anakam (13)	2.4±0.8	0.19±0.04	(Kusumaningtyas et al., 2019)
Sian Ka'an, Mexico (14)	17.50%	NA	(Adame et al., 2013)

Sedimentary Organic Carbon Stock Variability

To see the spatial variability of sedimentary organic carbon stock, we standardised the carbon stocks to 1m depth. For the sediment cores which have a depth of less than 1m, we extrapolated the C_{org} stocks to 1m depth. In this study, the sedimentary carbon stock varied among different sites as shown in Figure 4. The sedimentary carbon stock in Core M1 is 115 Mg C ha^{-1}, Core C1 is 189 Mg C ha^{-1}, Core C2 is 195 Mg C ha^{-1}, Core G1 is 181 Mg C ha^{-1}, Core G2 is 131 Mg C ha^{-1} and Core G3 is 135 Mg C ha^{-1}. The average sedimentary carbon storage per unit area for Coringa mangroves is 158±34.60 Mg C ha^{-1}. The area occupied by the Coringa mangroves forest including very dense and moderate forests is 11,822 ha (Ramana Murty et al., 2011). This gives a total belowground sedimentary stock of 1,867,876 Mg C (or 1.86 Tg C) for Coringa mangrove ecosystems. Spatial variation of sedimentary carbon stocks is found to be significantly different among various sites (F_{stat}=8.2; F_{crit}=2.28, p<0.01).

The maximum carbon stock has been found in Coringa mangroves (Core C1 and C2). The reason might be the presence of dense vegetation at this site which results in the trapping of material by mangrove root systems causing accumulation of sediments, providing stability in the muddy waterlogged soil which reduces the various hydrological impacts (like the flow of the river and tidal water) (Alongi, 2014; Kristensen et al., 2008). This process causes more deposition of organic carbon as compared to the less/or non-vegetated area. Moreover, the stagnant and non-flushing conditions of the water in Coringa creek (Tripathy et al., 2005) might cause an enhancement in its organic carbon content and thus stock. This is followed by Gaderu mangroves, with different stock in different sub-settings like more carbon stock in Core G1 (estuarine influence), followed by Core G3 (marine) and Core G2 (tidal) i.e., the mangroves near estuary have more organic carbon content (hence carbon stock) than a marine which is in accordance to the general trends.

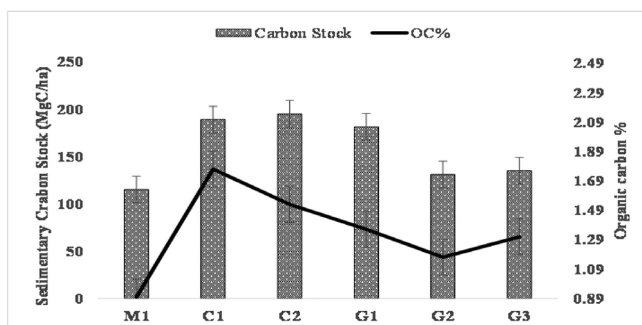


Figure 4: Spatial variation of sedimentary carbon stock in Coringa mangroves.

Despite being pristine, Core G3 has comparatively lower carbon stock than the rest of the mangroves which might be due to its low value of organic carbon content. Another reason might be the monotypic nature of this forest site (comprised mostly of Rhizophora only) while Coringa mangroves are comprised of mixed vegetation types (including *Avicennia marina, Avicennia officinalis, and Excoecaria agallocha,* etc.). The mixed type of vegetation has a mixture of various types of mangrove roots that may decrease the transfer of sediment produced by the tidal and hydrological regimes (Pérez et al., 2017). The other reason may be attributed to its proximity to the mouth of the Bay of Bengal and hence subjected to more flushing.

The lowest carbon stock can be seen in Matlapalem mangroves (Core M1) which might be due to its degraded forest condition. Degraded forests have loose soil conditions which are exposed to the atmosphere; hence the soils are susceptible to oxidation, also loose soil is not capable of holding the soils tightly. The hydrological mechanisms in less/or non-vegetated mangrove forests accelerate the transportation of sediments and materials to the adjacent areas. The other reason could be the lowest TOC content in Matlapalem and hence low carbon stock. Thus, spatial variation of carbon stock in Coringa mangroves suggests that the stock is maximum in the densely forested mangroves (Coringa) followed by moderately vegetated Gaderu forest and least in degraded forests of Matlapalem mangrove. In our study, the relatively pristine mangrove (Core G3) shows less carbon stock than Coringa (C1, C2) and G1 because of their proximity to the Bay of Bengal. A similar observation has been reported in Gujarat mangroves, where stock analysis reveals that dense mangroves were found to have maximum carbon stock (87.83 t ha^{-1}) followed by moderate mangroves (36.99 t ha^{-1}) and sparse mangroves (44.08 t ha^{-1}) showing the role of dense mangroves in sequestering carbon than sparse and degraded ones (Pandey & Pandey, 2013).

Sedimentary carbon storage in Coringa mangroves has been compared with other mangroves worldwide (Figure 5). The carbon stored in Coringa mangroves is higher than in Pichavaram, India (Sappal, 2016; Gnanamoorthy et al., 2019a) and Bhitarkanika but lower than in Sundarbans, Bangladesh, China,

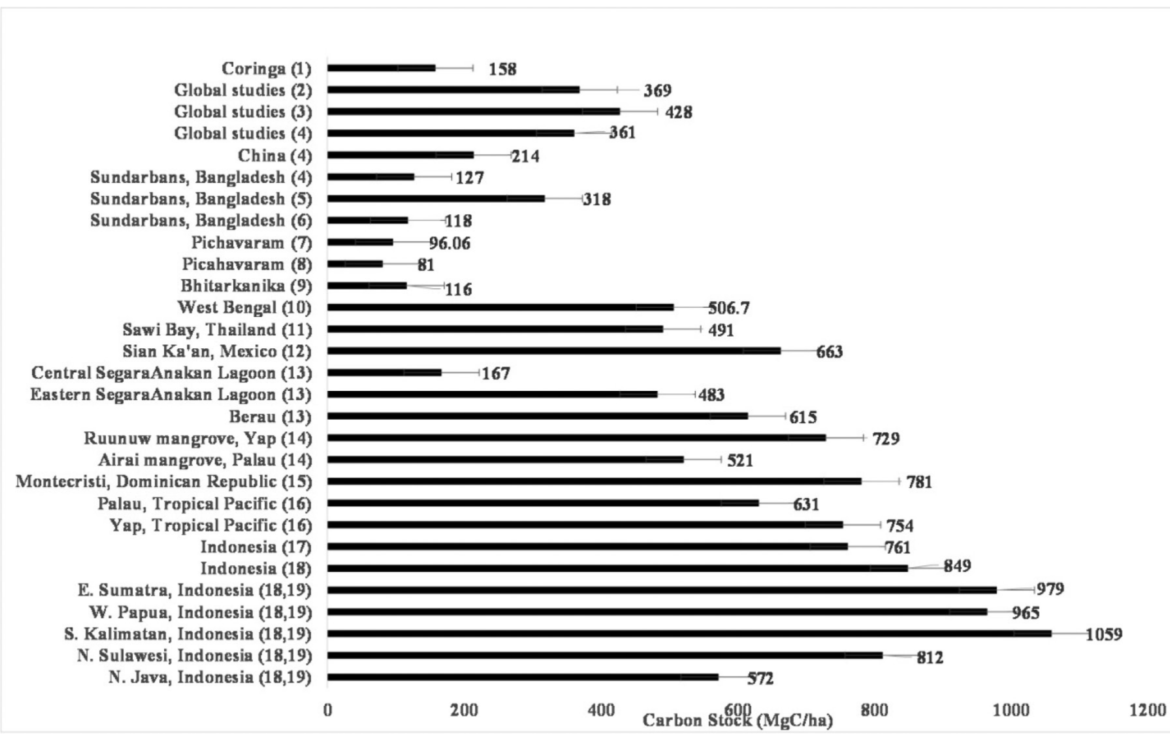


Figure 5: Comparison of sedimentary carbon stock of Coringa mangroves with other mangroves worldwide. 1) Present study; 2) Jardine & Siikamäki, 2014; 3) IPCC, 2014; 4) Sanderman et al., 2018; 5) Akther et al., 2021; 6) Atwood et al., 2017; 7) Gnanamoorthy et al., 2019; 8) Sappal, 2016; 9) Bhomia et al., 2016; 10) Ray et al., 2011; 11) Alongi, 2012; 12) Adame et al., 2013; 13) Kusumaningtyas et al., 2019; 14) Kauffman et al., 2011a; 15) Kauffman et al., 2014; 16) Donato et al., 2012; 17) Alongi et al., 2016; 18) Murdiyarso et al., 2015; 19) Donato et al., 2011.

Mexico, and other mangroves worldwide. Also, the sedimentary carbon storage in Coringa mangroves was quantitatively lower than the sediment carbon storage of other mangroves worldwide (Figure 5). The probable reason for the differences in carbon stock could be the inconsistency of the coring depth in the available literature and also in the present study. This could be corrected by standardising the collected core length to one uniform depth (~1m) for coring which practically is very difficult to achieve because of the extensive below and above ground root network which interferes with the coring process. The other reason for the carbon stock variability is differences in organic carbon content which varies significantly from <3% (in Indian and Bangladesh mangroves) to >20% (Mexican and Indonesian mangroves) (data from Donato et al., 2011; Adame et al., 2013; Kauffman et al., 2014; Murdiyarso et al., 2015). The spatial distribution of carbon stock in mangroves varied substantially. For example, higher organic carbon stock has been observed in West Africa than in East African nations (Sanderman et al., 2018). The opposite has been observed in the study by Jardine & Siikamäki (2014). Such type of differences and inconsistencies were also seen in Columbia, Sri Lanka, and many countries bordering the Red Sea. These incongruities might be most likely due to the lack of data in those regions during the time of analysis (Jardine & Siikamäki, 2014). It is to be noted that the total carbon storage is also determined by the total area covered by the mangroves. For example, among the top 25 nations holding organic carbon stock in mangroves, there was almost an even split between the countries having smaller mangrove areas having high organic carbon density and also other nations which have large mangrove cover with low carbon density as shown in a study by Sanderman et al. (2018). Indonesian mangroves are the exception in this case and show the largest mangrove area, which also has the highest carbon stocks making Indonesia the only mangroves holding approximately 25% of the world's mangrove organic carbon stocks.

Also, some mangroves do not have much consistency in organic carbon content and stock values. For example, organic carbon content in Indonesian mangroves is 10.45% with a carbon stock value of 849 Mg C ha^{-1}, in Airai mangrove, Palau OC content is 18.26% with carbon stock of 521 Mg C ha^{-1}, Montecristi Province has an organic value of 20% with a stock value of 781 Mg C ha^{-1}, Sian Ka'an Mexica with OC value of 17.50% with a stock value of 552 Mg C ha^{-1}, 5.70% in Berau mangroves (615 Mg C ha^{-1}) and 7.70% in Eastern Segara Anakan lagoon (483 Mg C ha^{-1}), respectively. Similarly, in the present study, Coringa mangroves have lower organic carbon content (1.30%) as compared to (2.84%) Pichavaram mangroves but have comparatively higher carbon stock of 158 Mg C ha^{-1} than Pichavaram mangroves 96.06 Mg C ha^{-1}. These studies show that some mangroves have high organic carbon content but relatively lower carbon stock and vice versa. So, we can conclude that sedimentary organic carbon content does not always translate into sequester carbon but other factors like soil conditions, soil particle size, trampling by animals, and various local environmental settings like land use patterns, etc. do play an important role in affecting the soil carbon stock.

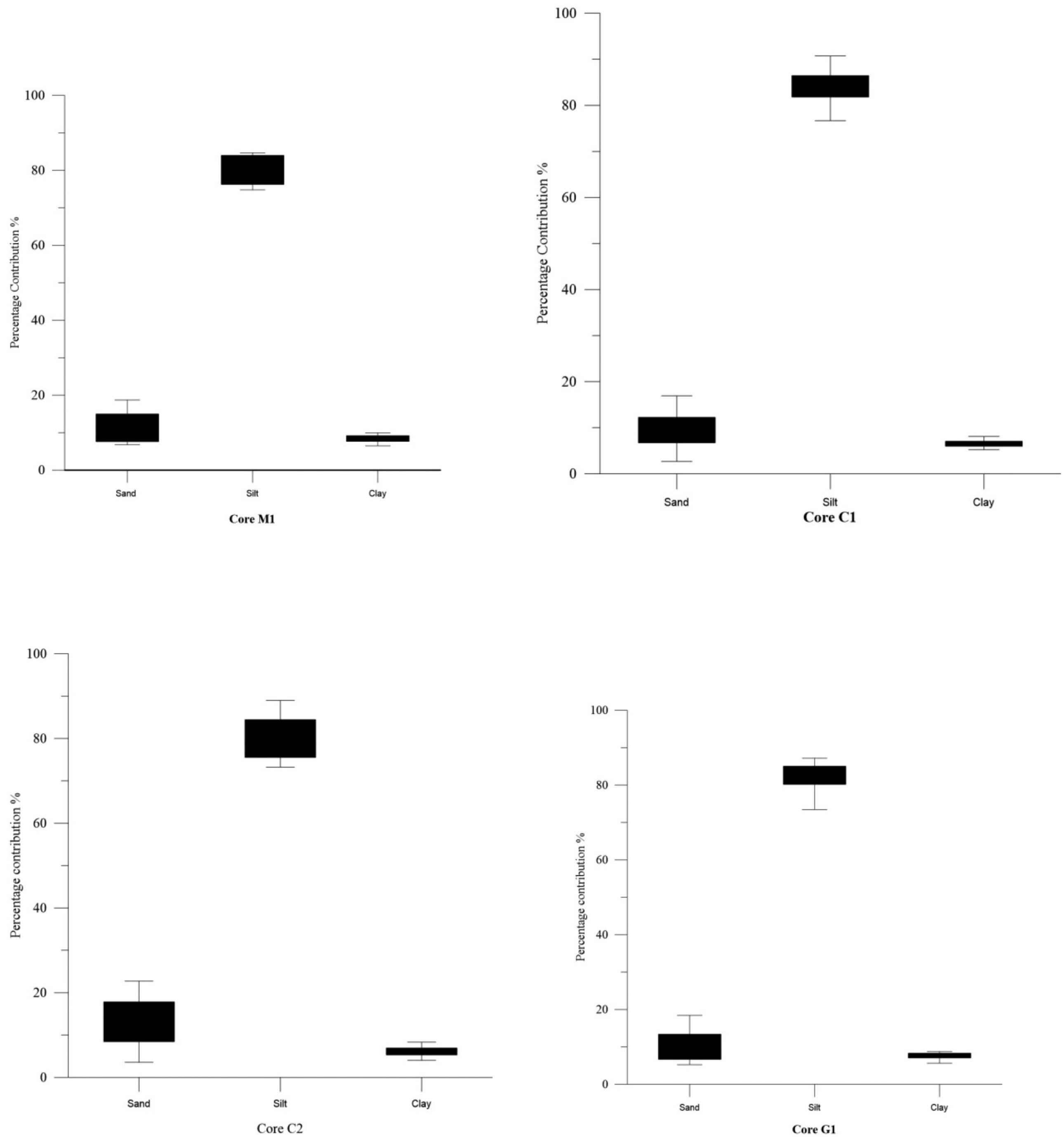
Sediment Textural Controls on Carbon Biogeochemistry

The sediments of Gautami-Godavari mangroves are abundant in silt fractions as compared to clay and sand. The mean values range from 7.72±7.46% to 30.46±19.42% for sand, 64.19±18.13 to 84.4±4.0% for silt, and 5.36±1.47% to 11.24±3.6% for clay fraction. The average % compositions of the different textural classes for the Gautami-Godavari mangroves are shown in Figure 6. The maximum sand percentage is found in Core B1 (KKD bay) and the minimum in Core G3. The maximum silt percentage is found in C1 and the minimum in Core A1. The maximum clay content is found in Core A1 and the minimum is found in Core B1.

To identify the possible relationship among different sediment fractions i.e., grain size (sand, silt, and clay) and organic carbon content Pearson's correlation analysis was used (Table 4). The test results were testified with a confidence level of 99% and *p* values of 0.01. The result shows that organic carbon content does not have a significant correlation with any of the grain size parameters, which signifies that no definite relationship is observed between C_{org} content and the abundance of finer sediment fractions in Coringa mangrove sediments. It is reported in previous literature that higher OM content tends to correlate with higher content of mud because the latter has more surface area and a greater number of available complexing and bindings sites (Magni et al., 2008). However, the clay/ or silt content of Coringa mangroves does not seem to govern the sedimentary organic carbon. Clay does not show any correlation with C_{org}% in most of the core but shows a significant negative correlation with Core C1 and G3. An interesting positive correlation has been observed between silt and C_{org} content in Core G3. This shows that sediment composition does not regulate the carbon content. Our study of textural control of sediments is found to be consistent with several other studies which show an inverse correlation between grain size and C_{org} content in sediments (Anderson, 1988; Mayer, 1994; Oades, 1988; Tiessen et al., 1984). The correlation between grain size C_{org} and grain size is mainly due to the stabilization of OM by adsorption or due to the hydrodynamic equivalence between organic particles and fine grains fractions (Pedersen & Calvert, 1990).

Organic Carbon Stock and Associated Carbon Dioxide Emissions from Coringa Mangroves: Climate Change Perspective

The soil organic carbon pool is an important factor of greenhouse gas emission as those are the substrate of carbon sources (CO_2 and acetate). They produce methane gas via the process of methanogenesis and even for heterotrophs. Any type of disturbance in the



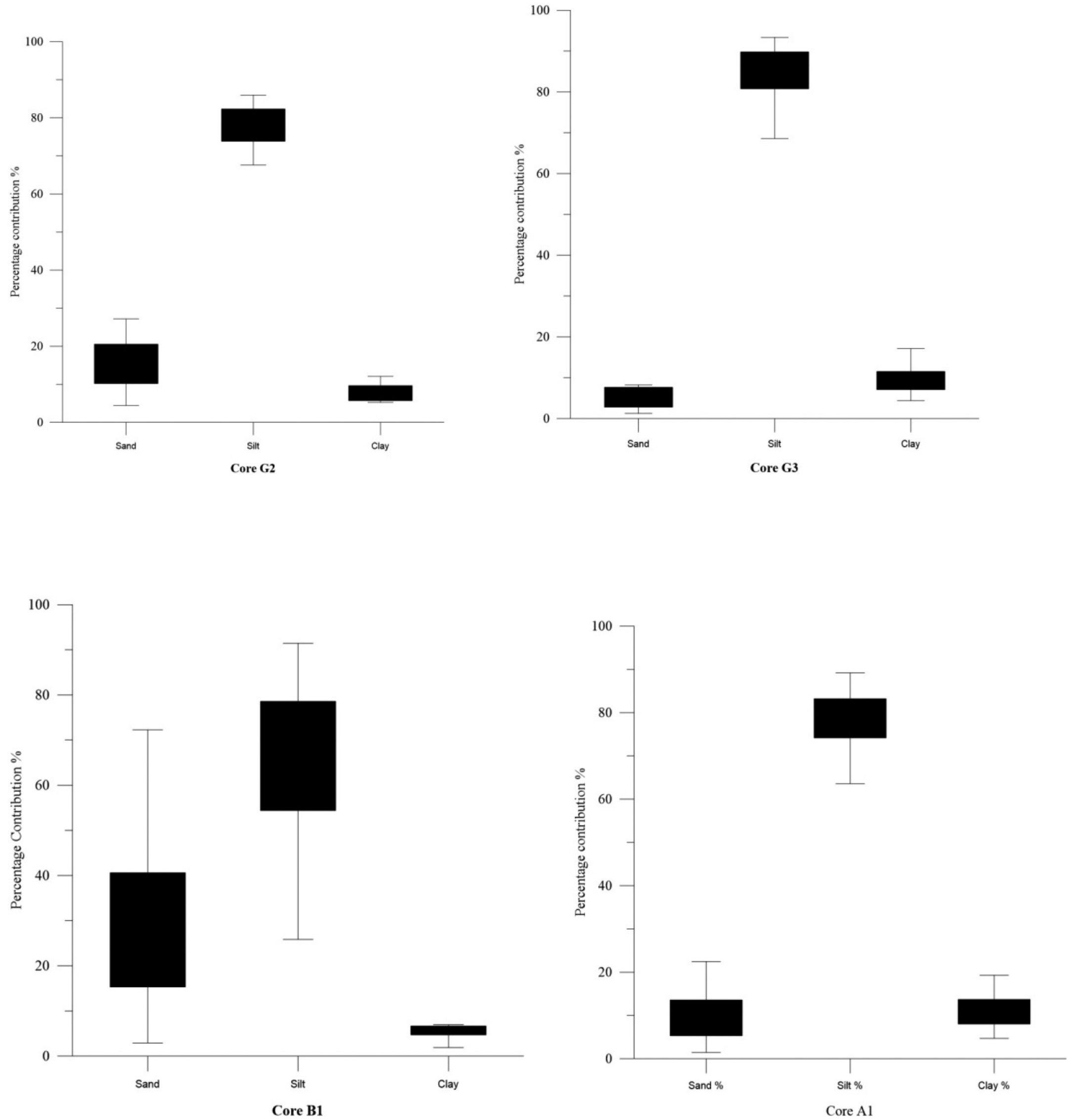


Figure 6: Textural characteristics of the sediment cores from the Gautami-Godavari mangrove ecosystem.

natural mangrove ecosystem like land use land cover changes, industrial discharge of effluents, rapid increase in urbanisation, and sewage flow into these ecosystems disturbs the previously stored carbon in mangrove soils and can lead to GHGs emissions. This type of disturbance has also been observed in Coringa mangroves where the extent of medium and sparse mangroves is found to be decreased from 5267 ha to 3828 ha and 1726 ha to 928 ha between the years 1988 to 2010 (Ramana Murty et al., 2011). This considerable decline in the mangrove areas is observed due to an increase in aquacultural activities going on in the protected areas (Ramana Murty et al., 2009). One study reveals that in the Godavari region, the area under aquacultural ponds shows a significant increase from 2985 ha to 7067 ha between the year 1990 to 2005 (Rajitha et al., 2010). This type of anthropogenic disturbances and continuous shrinkage in the Coringa mangrove ecosystem over time could disturb the previously sequestered organic carbon in mangrove sediments leading to the emission of Greenhouse gases. Sarma et al. (2011) calculated the carbon dioxide emissions in the Godavari estuary for the year 2009 where carbon dioxide flux was about 52.6 mol C m^{-2} y^{-1}. This estimated emission of carbon from the Godavari estuary alone surpasses (by almost 2 times) the assessed value of the entire subtropical and tropical band of 25.72 mol C m^{-2} y^{-1}) (Borges et al., 2005). This indicates that coastal ecosystems could be a significant source of carbon dioxide and mangrove ecosystems keep a check on this emission by storing them in their biomass and sediments. The present reveals that Coringa mangroves store considerable carbon stock which is

Table 4: Correlation between sediment texture and organic carbon as depicted by 2- tailed Person's correlation (significance level 0.01)

Core M1	*Corg%*	*Sand%*	*Silt%*	*Clay%*
Corg%	1.00			
Sand%	–0.16	1.00		
Silt%	0.22	–0.97**	1.00	
Clay%	–0.19	–0.44	0.21	1.00

Core Cl	*Corg%*	*Sand%*	*Silt%*	*Clay%*
Corg%	1.00			
Sand%	0.33	1.00		
Silt%	–0.23	–0.98**	1.00	
Clay%	–0.57**	–0.45*	0.27	1.00

Core C2	*Corg%*	*Sand%*	*Silt%*	*Clay%*
Corg%	1.00			
Sand%	–0.23	1.00		
Silt%	0.26	–0.99**	1.00	
Clay%	–0.08	–0.44*	0.30	1.00

Core G1	*Corg%*	*Sand%*	*Silt%*	*Clay%*
Corg%	1.00			
Sand%	0.07	1.00		
Silt%	0.04	–0.99**	1.00	
Clay%	–0.19	–0.36	0.19	1.00

Core G2	*Corg%*	*Sand%*	*Silt%*	*Clay%*
Corg%	1.00			
Sand%	0.69**	1.00		
Silt%	–0.68**	-0.96**	1.00	
Clay%	–0.47**	-0.74**	0.51	1.00

Core G3	*Corg%*	*Sand%*	*Silt%*	*Clay%*
Corg%	1.00			
Sand%	–0.27	1.00		
Silt%	0.51**	–0.92**	1.00	
Clay%	–0.71**	0.26	–0.61**	1.00

Core Bl	*Corg%*	*Sand%*	*Silt%*	*Clay%*
Corg%	1.00			
Sand%	–0.01	1.00		
Silt%	0.02	–0.99**	1.00	
Clay%	–0.074	–0.88**	0.864*	1.00

CoreAl	*Corg%*	*Sand%*	*Silt%*	*Clay%*
Corg%	1.00			
Sand%	-0.16	1.00		
Silt%	0.23	-0.84**	1.00	
Clay%	-0.18	-0.02	-0.53**	1.00

consistent with the carbon stock in other Indian as well as global mangroves. Since sedimentary carbon stock refers to the amount of carbon stored in the sediments and represents the amount of carbon that is susceptible to be emitted as carbon dioxide (due to related OM oxidation) upon degradation and removal of mangroves. Coringa mangroves owing to their significant amount of stored carbon have the potential to release this carbon upon disturbance (natural and anthropogenic) and represents the equivalent CO_2 emission of 579.9 Mg CO_2e ha^{-1}. This carbon equivalent CO_2 of Coringa have been compared across various mangroves around the globe to their capacity to emit carbon dioxide with respect to other mangroves worldwide. From Figure 7, it is clear that the highest amount of carbon storage and hence maximum CO_2 equivalent has been observed for Montecristi, the Dominican Republic followed by Ruunuw (Micronesia) followed by Berau. Sundarban Bangladesh has the potential to emit carbon more than China. In India, Coringa mangroves (present study) show comparatively more carbon stock and hence equivalent CO_2 emissions than that of Bhitarkanika, Pichavaram, and Tamil Nadu. The higher carbon stock in Coringa mangroves reveals their importance in storing carbon and hence could have relevance on national scale too and play an important role in climate change mitigation. It is to be noted that Godavari estuary (feeding Coringa mangroves) is characterised under reduced aggradation i.e., they can no longer continue to keep up with a local rise in the sea level (Ramana Murty et al., 2011). This makes this ecosystem of utmost importance with respect to the study of carbon dynamics. Importance should be given to increasing the biomass of the Coringa mangrove ecosystem which could be proved helpful for the increasing carbon sequestration capacity of Coringa mangroves and advantageous for mitigating sea level rise (Rao, 2009).

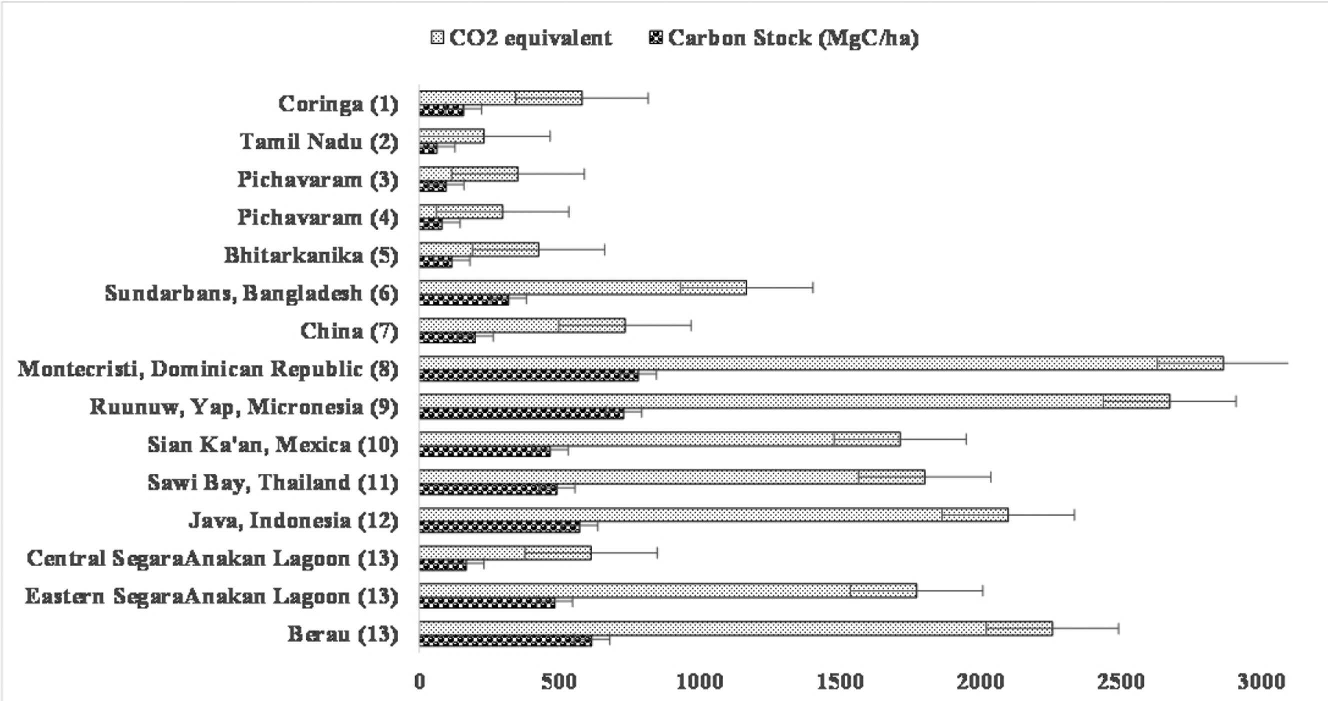


Figure 7: The organic carbon stock in sediments and equivalent CO_2 emission of various mangroves across the world. 1) Present study; 2) Kathiresan et al., 2013; 3) Gnanamoorthy et al., 2019b; 4) Sappal, 2016; 5) Bhomia et al., 2016; 6) Akther et al., 2021; 7) Wang et al., 2013; 8) Kauffman et al., 2014; 9) Kauffman et al., 2011a; 10) Adame et al., 2013a; 11) Daniel M. Alongi, 2012; 12) Donato et al., 2011; Murdiyarso et al., 2015; 13) Kusumaningtyas et al., 2019.

Conclusion

This study highlights the importance of mangroves in carbon storage and their spatial variation in various environmental settings. The present study provides the baseline carbon stock assessment in the Coringa mangrove forest. Maximum carbon stock has been found at aquaculture sites. Among different mangroves, the highest carbon stock has been found in dense mangroves (Coringa), followed by moderately vegetated mangroves, and then degraded and deforested mangroves (Matlapalem). This reveals the significance of densely vegetated mangrove ecosystems in effective filtration and sequestration of organic carbon and hence prevents the transportation of carbon back to the atmosphere and coastal ocean. The lowest organic carbon in degraded mangroves suggests that degradation and deforestation activities affect the organic carbon content significantly. The study also reveals that organic carbon is being regulated by other processes, rather than grain size parameters. The organic carbon content and carbon stock of Coringa mangroves are found to be relevant when compared to other mangrove ecosystems and hence their potential to release carbon dioxide, upon disturbance are also relevant. Continuous shrinkage in the Coringa mangroves has been observed over time which could release a significant amount of carbon dioxide into the atmosphere. Moreover, the Godavari estuary is characterised by aggradation, so it is difficult for it to keep up pace with the rise in local sea level. This indicates that Coringa mangroves are more vulnerable to climate change. More focus should be given to conserving the existing increased biomass of this mangrove ecosystem which might help increase the carbon sequestration capacity of this mangrove. This study highlights there is a dire need for a more representative region-based study to improve the mangrove carbon budget on a global scale.

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References

Adame, M.F., Kauffman, J.B., Medina, I., Gamboa, J.N., Torres, O., Caamal, J.P., Reza, M., and Herrera-Silveira, J.A., 2013. Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. *PloS One*, **8(2):** e56569. https://doi.org/10.1371/JOURNAL.PONE.0056569

Akther, S.M., Islam, M.M., Hossain, M.F. and Parveen, Z., 2021. Fractionation of organic carbon and stock measurement in the Sundarbans Mangrove. *American Journal of Climate Change*, **10(4):** 561-580. https://doi.org/10.4236/AJCC.2021.104028

Alongi, D.M., Murdiyarso, D., Fourqurean, J.W., Kauffman, J.B., Hutahaean, A., Crooks, S., Lovelock, C.E., Howard, J., Herr, D., Fortes, M., Pidgeon, E. and Wagey, T., 2016. Indonesia's blue carbon: A globally significant and vulnerable sink for seagrass and mangrove carbon. *Wetlands Ecology and Management*, **24(1):** 3-13. https://doi.org/10.1007/S11273-015-9446-Y/FIGURES/4

Alongi, D.M., 2012. Carbon sequestration in mangrove forests. *In:* Carbon Management, **3(3):** 313-322. Future Science Ltd. London, UK. https://doi.org/10.4155/cmt.12.20

Alongi, D.M., 2014. Carbon cycling and storage in mangrove forests. *Annual Review*s, **6:** 195-219. https://doi.org/10.1146/annurev-marine-010213-135020

Anderson, D.W., 1988. The effect of parent material and soil development on nutrient cycling in temperate ecosystems. *Biogeochemistry*, **5(1):** 71-97. https://doi.org/10.1007/BF02180318

Atwood, T.B., Connolly, R.M., Almahasheer, H., Carnell, P.E., Duarte, C.M., Lewis, C.J.E., Irigoien, X., Kelleway, J.J., Lavery, P.S., Macreadie, P.I., Serrano, O., Sanders, C.J., Santos, I., Steven, A.D.L. and Lovelock, C.E., 2017. Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change*, **7(7):** 523-528. https://doi.org/10.1038/nclimate3326

Banerjee, K., Sahoo, C.K., Bal, G., Mallik, K., Paul, R. and Mitra, A., 2020. High blue carbon stock in mangrove forests of Eastern India. *Tropical Ecology*, **61(1):** 150-167. https://doi.org/10.1007/S42965-020-00072-Y

Bhomia, R.K., Mackenzie, R.A., Murdiyarso, D., Sasmito, S.D. and Purbopuspito, J., 2016. Impacts of land use on Indian mangrove forest carbon stocks: Implications for conservation and management. *Ecological Applications : A Publication of the Ecological Society of America*, **26(5)**: 1396-1408. https://doi.org/10.1890/15-2143

Boone Kauffman, J., Arifanti, V.B., Hernández Trejo, H., del Carmen Jesús García, M., Norfolk, J., Cifuentes, M., Hadriyanto, D. and Murdiyarso, D., 2017. The jumbo carbon footprint of a shrimp: Carbon losses from mangrove deforestation. *Frontiers in Ecology and the Environment*, **15(4):** 183-188. https://doi.org/10.1002/FEE.1482

Borges, A.V., Delille, B. and Frankignoulle, M., 2005. Budgeting sinks and sources of CO_2 in the coastal ocean: Diversity of ecosystems counts. *Geophysical Research Letters*, **32(14):** 1-4. https://doi.org/10.1029/2005GL023053

Bouillon, S., Dahdouh-Guebas, F., Rao, A.V.V.S., Koedam, N. and Dehairs, F., 2003. Sources of organic carbon in mangrove sediments: Variability and possible ecological implications. *Hydrobiologia*, **495:** 33-39. https://doi.org/10.1023/A:1025411506526

Bournazel, J., Kumara, M.P., Jayatissa, L.P., Viergever, K., Morel, V. and Huxham, M., 2015. The impacts of shrimp farming on land-use and carbon storage around Puttalam lagoon, Sri Lanka. *Ocean & Coastal Management*, **113:** 18-28. https://doi.org/10.1016/J.OCECOAMAN.2015.05.009

Carnell, P.E., Windecker, S.M., Brenker, M., Baldock, J., Masque, P., Brunt, K. and Macreadie, P.I., 2018. Carbon stocks, sequestration, and emissions of wetlands in south eastern Australia. *Global Change Biology*, **24(9):** 4173-4184. https://doi.org/10.1111/GCB.14319

Donato, D.C., Kauffman, J.B., Mackenzie, R.A., Ainsworth, A. and Pfleeger, A.Z., 2012. Whole-island carbon stocks in the tropical Pacific: Implications for mangrove conservation and upland restoration. *Journal of Environmental Management,* **97(1):** 89-96. https://doi.org/10.1016/j.jenvman.2011.12.004

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. and Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, **4(5):** 293-297. https://doi.org/10.1038/ngeo1123

Drewry, J.J., Cameron, K.C. and Buchan, G.D., 2008. Pasture yield and soil physical property responses to soil compaction from treading and grazing - A review. *Australian Journal of Soil Research*, **46(3):** 237-256. https://doi.org/10.1071/SR07125

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I. and Marbà, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, **3(11):** 961-968. https://doi.org/10.1038/NCLIMATE1970

FSI, 2021. *Welcome To Forest Survey of India*. *In:* Ministry of Environment Forest and Climate Change. https://fsi.nic.in/forest-report-2021-details

Giri, C., Zhu, Z., Tieszen, L.L., Singh, A., Gillette, S. and Kelmelis, J.A., 2008. Mangrove forest distributions and dynamics (19752005) of the tsunami-affected region of Asia. *Journal of Biogeography*, **35(3):** 519-528. https://doi.org/10.1111/J.1365-2699.2007.01806.X

Gnanamoorthy, P., Selvam, V., Ramasubramanian, R., Chakraborty, S., Pramit, D. and Karipot, A., 2019a. Soil organic carbon stock in natural and restored mangrove forests in Pichavaram south-east coast of India. *Indian Journal of Geo Marine Sciences*, **48(05):** 801-808. http://nopr.niscair.res.in/handle/123456789/47407

Gnanamoorthy, P., Selvam, V., Ramasubramanian, R., Nagarajan, R., Chakraborty, S., Deb Burman, P.K. and Karipot, A., 2019b. Diurnal and seasonal patterns of soil CO2 efflux from the Pichavaram mangroves, India. *Environmental monitoring and assessment*, **191(4):** 1-12.

Harishma, K.M., Sandeep, S. and Sreekumar, V.B., 2020. Biomass and carbon stocks in mangrove ecosystems of Kerala, southwest coast of India. *Ecological Processes*, **9(1):** 31. https://doi.org/10.1186/S13717-020-00227-8

Howard, P.J.A., Loveland, P.J., Bradley, R.I., Dry, F.T., Howard, D.M. and Howard, D.C., 1995. The carbon content of soil and its geographical distribution in Great Britain. *Soil Use and Management*, **11(1):** 9-15. https://doi.org/10.1111/J.1475-2743.1995.TB00488.X

IPCC, 2014. https://www.ipcc.ch/2014/

Jardine, S.L. and Siikamäki, J.V., 2014. A global predictive model of carbon in mangrove soils. *Environmental Research Letters*, **9(10):** 104013. https://doi.org/10.1088/1748-9326/9/10/104013

Jennerjahn, T.C. and Ittekkot, V., 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. *Naturwissenschaften*, **89(1):** 23-30. https://doi.org/10.1007/s00114-001-0283-x

Kathiresan, K., Anburaj, R., Gomathi, V. and Saravanakumar, K., 2013. Carbon sequestration potential of Rhizophora mucronata and Avicennia marina as influenced by age, season, growth and sediment characteristics in southeast coast of India. *Journal of Coastal Conservation*, **17(3):** 397-408. https://doi.org/10.1007/S11852-013-0236-5/FIGURES/2

Kauffman, J.B., Heider, C., Cole, T.G., Dwire, K.A. and Donato, D.C., 2011a. Ecosystem carbon stocks of micronesian mangrove forests. *Wetlands*, **31(2):** 343-352. https://doi.org/10.1007/s13157-011-0148-9

Kauffman, J.B., Heider, C., Cole, T.G., Dwire, K.A. and Donato, D.C., 2011b. Ecosystem carbon stocks of micronesian mangrove forests. *Wetlands*, **31(2):** 343-352. https://doi.org/10.1007/S13157-011-0148-9/TABLES/4

Kauffman, J.B., Heider, C., Norfolk, J. and Payton, F., 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. *Ecological Applications*, **24(3):** 518-527. https://doi.org/10.1890/13-0640.1

Kristensen, E., Bouillon, S., Dittmar, T. and Marchand, C., 2008. Organic carbon dynamics in mangrove ecosystems: A review. *Aquatic Botany*, **89(2):** 201-219. https://doi.org/10.1016/J.AQUABOT.2007.12.005

Kusumaningtyas, M.A., Hutahaean, A.A., Fischer, H.W., Pérez-Mayo, M., Ransby, D. and Jennerjahn, T.C., 2019. Variability in the organic carbon stocks, sources, and accumulation rates of Indonesian mangrove ecosystems. *In:* Estuarine, Coastal and Shelf Science, **218:** 310-323. https://doi.org/10.1016/j.ecss.2018.12.007

MacKenzie, R.A., Foulk, P.B., Klump, J.V., Weckerly, K., Purbospito, J., Murdiyarso, D., Donato, D.C. and Nam, V.N., 2016. Sedimentation and belowground carbon accumulation rates in mangrove forests that differ in diversity and land use: a tale of two mangroves. *Wetlands Ecology and Management*, **24(2):** 245-261. https://doi.org/10.1007/S11273-016-9481-3/FIGURES/6

Magni, P., De Falco, G., Como, S., Casu, D., Floris, A., Petrov, A.N., Castelli, A. and Perilli, A., 2008. Distribution and ecological relevance of fine sediments in organic-enriched lagoons: The case study of the Cabras lagoon (Sardinia, Italy). *Marine Pollution Bulletin*, **56(3)**: 549-564. https://doi.org/10.1016/j.marpolbul.2007.12.004

Mayer, L.M., 1994. Surface area control of organic carbon accumulation in continental shelf sediments. *Geochimica et Cosmochimica Acta*, **58(4):** 1271-1284. https://doi.org/10.1016/0016-7037(94)90381-6

McLeod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H. and Silliman, B.R., 2011. A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, **9(10):** 552-560. https://doi.org/10.1890/110004

Mizanur Rahman, M., Nabiul Islam Khan, M., Fazlul Hoque, A.K. and Ahmed, I., 2015. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. *Wetlands Ecology and Management*, **23(2):** 269-283. https://doi.org/10.1007/S11273-014-9379-X

Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D. C., Manuri, S., Krisnawati, H., Taberima, S. and Kurnianto, S., 2015. The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, **5(12):** 1089-1092. https://doi.org/10.1038/nclimate2734

Nam, V.N., Sasmito, S.D., Murdiyarso, D., Purbopuspito, J. and MacKenzie, R.A., 2016. Carbon stocks in artificially and naturally regenerated mangrove ecosystems in the Mekong Delta. *Wetlands Ecology and Management*, **24(2):** 231-244. https://doi.org/10.1007/S11273-015-9479-2

Nguyen H.T. et al., 2014. *Current socio-economic and environmental conditions of agroforestry system in Ca Mau province*. MDRI Cantho University, ICRAF. https://scholar.google.co.in/scholar?hl=en&as_sdt=0%2C5&q=Current+socio-economic+and+environmental+conditions+of+agroforestry+system+in+Ca+Mau+

province%2C+MDRI+Cantho+Uni%02versity%2C+ICRAF.&btnG=

Oades, J.M., 1988. The retention of organic matter in soils. *Biogeochemistry,* **5(1):** 35-70. https://doi.org/10.1007/BF02180317

Pandey, C.N. and Pandey, R., 2013. Carbon sequestration in mangroves of Gujarat, India. *International Journal of Botany and Research*, **3(2):** 57-70.

Pedersen, T.F. and Calvert, S.E., 1990). Anoxia vs. productivity: What controls the formation of organic-carbon-rich sediments and sedimentary rocks? *AAPG Bulletin*, **74(4):** 454-466. https://doi.org/10.1306/0C9B232B-1710-11D7-8645000102C1865D

Pérez, A., Gutiérrez, D., Saldarriaga, M.S. and Sanders, C.J., 2017. Hydrological controls on the biogeochemical dynamics in a Peruvian mangrove forest. *Hydrobiologia*, **803(1):** 69-86. https://doi.org/10.1007/s10750-017-3118-2

Prasad, M.B. and Ramanathan, A.L., 2009. Organic matter characterization in a tropical estuarine-mangrove ecosystem of India: Preliminary assessment by using stable isotopes and lignin phenols. *Estuarine, Coastal and Shelf Science*, **84(4):** 617-624. https://doi.org/10.1016/j.ecss.2009.07.029

Priya, N., 2019. Distribution, Sources and Fate of Carbon in the Gautami-Godavari Estuarine Mangrove Ecosystem, Andhra Pradesh, India. Ph.D. Thesis, Jawaharlal Nehru University.

Rajitha, K., Mukherjee, C.K., Chandran, R.V. and Mohan, M.M.P., 2010. Land-cover change dynamics and coastal aquaculture development: A case study in the East Godavari delta, Andhra Pradesh, India using multi-temporal satellite data. *International Journal of Remote Sensing*, **31(16):** 4423-4442. https://doi.org/10.1080/01431160903277456

Ramana Murty, M.V., Kumar, C.R., Reddy, K.M. and Ramasubramanian, R., 2011. Geospatial analysis of Coringa-marine protected area, Andhra Pradesh, India. *Researchgate.Net*, **04(08):** 2041304. https://www.researchgate.net/profile/Ramana-Murty-M-V/publication/343064351_Geospatial_Analysis_of_Coringa_-_Marine_Protected_Area_Andhra_Pradesh_India/links/5f1542bf92851c1eff21804e/Geospatial-Analysis-of-Coringa-Marine-Protected-Area-Andhra-Pradesh-India.pdf

Ranjan, R.K., Routh, J., Ramanathan, AL. and Klump, J.V., 2011. Elemental and stable isotope records of organic matter input and its fate in the Pichavaram mangrove–estuarine sediments (Tamil Nadu, India). *Marine Chemistry*, **126(1-4):** 163-172. https://doi.org/10.1016/J.MARCHEM.2011.05.005

Rao, R.G., 2009. Climate change mitigation through reforestation in Godavari mangroves in India. *International Journal of Climate Change Strategies and Management*, **1(4):** 340-355. https://doi.org/10.1108/17568690911002870/FULL/HTML

Ray, R., Ganguly, D., Chowdhury, C., Dey, M., Das, S., Dutta, M.K., Mandal, S.K., Majumder, N., De, T.K., Mukhopadhyay, S.K. and Jana, T.K., 2011. Carbon sequestration and annual increase of carbon stock in a mangrove forest. *Atmospheric Environment*, **45(28):** 5016-5024. https://doi.org/10.1016/j.atmosenv.2011.04.074

Ray, R.A. and Jana, T.K., 2017. Carbon sequestration by mangrove forest: One approach for managing carbon dioxide emission from coal-based power plant. *Atmospheric Environment*, **171:** 149-154. https://doi.org/10.1016/J.ATMOSENV.2017.10.019

Sahu, S.C., Suresh, H.S., Murthy, I.K. and Ravindranath, N.H., 2015. Mangrove area assessment in India: Implications of loss of mangroves. *Journal of Earth Science & Climatic Change*, **06(05):** 280. https://doi.org/10.4172/2157-7617.1000280

Sanderman, J., Hengl, T., Fiske, G., Solvik, K., Adame, M. F., Benson, L., Bukoski, J. J., et al., 2018. A global map of mangrove forest soil carbon at 30 m spatial resolution. *Environmental Research Letters*, **13(5):** 055002. https://doi.org/10.1088/1748-9326/AABE1C

Sappal S., 2016. Blue Carbon Dynamics in Pichavaram Mangrove Ecosystems, Tamil Nadu, India. Ph.D. Thesis, Jawaharalal Nehru University.

Sarma, V.V.S.S., Kumar, N.A., Prasad, V.R., Venkataramana, V., Appalanaidu, S., Sridevi, B., Kumar, B.S.K., et al., 2011. High CO_2 emissions from the tropical Godavari estuary (India) associated with monsoon river discharges. *Geophysical Research Letters*, **38(8):** L08601. https://doi.org/10.1029/2011GL046928

Satyanarayana, B., Raman, A.V., Dehairs, F., Kalavati, C. and Chandramohan, P., 2002. Mangrove floristic and zonation patterns of Coringa, Kakinada Bay, East Coast of India. *Wetlands Ecology and Management*, **10(1):** 25-37. https://doi.org/10.1023/A:1014345403103

Shaik, A.R., Biswas, H., Reddy, N.P.C., Rao, V.S., Bharathi, M.D. and Subbaiah, C.V., 2015. Time series monitoring of water quality and microalgal diversity in a tropical bay under intense anthropogenic interference (SW coast of the Bay of Bengal, India). *Environmental Impact Assessment Review*, **55:** 169-181. https://www.sciencedirect.com/science/article/pii/S0195925515000803

Siikamäki, J., Sanchirico, J.N., Jardine, S., McLaughlin, D. and Morris, D., 2013. Blue carbon: Coastal ecosystems, their carbon storage, and potential for reducing emissions. *Environment*, **55(6):** 14-29. https://doi.org/10.1080/00139157.2013.843981

Siikamäki, Sanchirico, J.N. and Jardine, S.L., 2012. Global economic potential for reducing carbon dioxide emissions from mangrove loss. *Proceedings of the National Academy of Sciences of the United States of America*, **109(36):** 14369-14374. https://doi.org/10.1073/pnas.1200519109

Tiessen, H., Stewart, J.W.B. and Hunt, H.W., 1984. Concepts of soil organic matter transformations in relation to organo-mineral particle size fractions. *Plant and Soil,* **76(1):** 287-295. https://doi.org/10.1007/BF02205587

Tripathy, S.C., Ray, A.K., Patra, S. and Sarma, V.V., 2005. Water quality assessment of Gautami-Godavari mangrove estuarine ecosystem of Andhra Pradesh, India during September 2001. *Journal of Earth System Science*, **114(2):** 185-190. https://doi.org/10.1007/BF02702020

Twilley, R.R., Chen, R.H. and Hargis, T., 1992. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. *Water, Air, & Soil Pollution*, **64(1-2):** 265-288. https://doi.org/10.1007/BF00477106

Vinod, K., Asokan, P.K., Zacharia, P.U., Ansar, C.P., Vijayan, G., Anasukoya, A., Kunhi Koya, V.A. and Nikhiljith, M., 2019. Assessment of biomass and carbon stocks in mangroves of Thalassery estuarine wetland of Kerala, South West Coast of India. *Journal of Coastal Research*, **86(sp1):** 209-217. https://doi.org/10.2112/SI86-031.1

Wang, G., Guan, D., Peart, M.R., Chen, Y. and Peng, Y., 2013. Ecosystem carbon stocks of mangrove forest in Yingluo Bay, Guangdong Province of South China. *Forest Ecology and Management*, **310:** 539-546. https://doi.org/10.1016/J.FORECO.2013.08.045

Wylynko, D., 1999. Prairie wetlands and carbon sequestration: Assessing sinks under Kyoto Protocol, Institute for Sustainable Development, Ducks Unlimited Canada, and Wetlands International, Winnipeg, Manitoba, Canada. http://iisd.ca/about/prodcat/ordering.htm