Highlights

1. The mean soil organic carbon (SOC) is lower in the Sundarbans than most mangroves.
2. Both salinity zone and forest type had a significant effect on SOC.
3. Irrespective of salinity zonation, the top 10 cm contained the highest SOC density.
4. Salinity, C: N and tree diameter were the best predictors of SOC variability.

Is soil organic carbon underestimated in the largest mangrove forest ecosystems? Evidence from the Bangladesh Sundarbans

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Abstract

Globally, mangroves sequester a large amount of carbon into the sediments, although spatial heterogeneity exists owing to a wide variety of local, regional, and global controls. Rapid environmental and climate change, including increasing sea-level rise, global warming, reduced upstream discharge and anthropogenic activities, are predicted to increase salinity in the mangroves, especially in the Bangladesh Sundarbans, thereby disrupting this blue carbon reservoir. Nevertheless, it remains unclear how salinity affects the belowground soil carbon despite the recognised effect on above ground productivity. To address this gap, research was undertaken in the Bangladesh Sundarbans to compare total soil organic carbon (SOC) across three salinity zones and to explore any potential predictive relationships with other physical, chemical properties and vegetation characteristics. Total SOC was significantly higher in the oligohaline zone (74.8 ± 14.9 Mg ha^{-1}), followed by the mesohaline (59.3 ± 15.8 Mg ha^{-1}), and polyhaline zone (48.3 ± 10.3 Mg ha^{-1}) (ANOVA, $F_{2, 500} = 118.9$, p <0.001). At all sites, the topmost 10 cm of soil contained higher SOC density than the bottom depths (ANOVA, $F_{3, 500} = 30.1$, p <0.001). On average, *Bruguiera sp.* stand holds the maximum SOC measured, followed by two pioneer species *Sonneratia apetala* and *Avicennia sp*. Multiple regression results indicated that soil salinity, organic C: N and tree diameter were the best predictor for the variability of the SOC in the Sundarbans (R^2 = 0.62). Despite lower carbon in the soil, the study highlights that the conservation priorities and low deforestation have led to less CO_2 emissions than most sediment carbon-rich mangroves in the world. The study also emphasised the importance of spatial conservation planning to safeguard the soil carbon-rich zones in the Bangladesh Sundarbans from anthropogenic tourism and development activities to support climate change adaptation and mitigation strategies.

Keywords: Soil organic carbon; salinity zones; soil depth; mangrove forest; the Sundarbans.

1. Introduction

Mangroves are recognised as one of the most carbon-dense forest types in the world due to their efficient carbon sequestration capacity into both above and below ground carbon pools (Donato et al., 2011; Alongi, 2012; Sanderman et al., 2018). Recent assessments of soil carbon suggest that mangrove ecosystems contain, on an average, between 856 and 1,023 Mg of carbon per hectare, with the majority (~85%) of this carbon stored in the soil (Donato et al., 2011; Pendleton et al., 2012; Sanderman et al., 2018; Kauffman et al., 2020). This large amount of soil carbon is of global importance due to its potential to store sequestered CO_2 emissions for the long term and help mitigate adverse effects of climate change (McLeod et al., 2011; Duarte et al., 2013; Abdullah et al., 2016). To recognise the importance of mangrove forests for carbon sequestration, United Nations Environmental Programme (UNEP) designated this ecosystem as "Blue Carbon" along with other coastal vegetated ecosystems such as seagrass meadows and saltmarshes (Nellemann et al., 2009; Lovelock and Duarte, 2019; Macreadie et al., 2019). This growing worldwide importance of mangroves has led to a substantial reduction of mangrove loss leading to reductions in CO_2 emissions in the last three decades (Friess et al., 2019). At the same time, mangroves have gained substantial traction in being managed, protected and restored as part of national and global climate change mitigation policies and actions including Nationally Determined Contributions (NDC) towards the Paris Agreement and climate action goal (goal 13) under United Nations Sustainable Development Goals (SDG) (Taillardat et al., 2018; Friess et al., 2020). However, variability and uncertainty in SOC estimation is a key barrier to the inclusion of mangroves (and other blue carbon) in national and international policy tools and frameworks.

Despite covering only 0.1% of the world's total landmass, mangroves sequester more carbon per unit area than any other natural ecosystems (Atwood et al., 2017; Lovelock and Duarte, 2019). With autochthonous inputs from the productive above-ground, mangrove soils store large quantities of carbon as a result of the low decomposition rate resulting from anoxic conditions (Donato et al., 2011; Alongi, 2012). Mangroves are also highly efficient traps for allochthonous inputs through their dense network of above ground roots. The rising elevation of mangroves in response to sea-level rise allows large accommodation spaces to sequester more carbon in the soil, which barely reaches saturation (Krauss et al., 2014; Rogers et al., 2019). Therefore, mangroves act as an efficient carbon store despite continuous threats from deforestation, land-use change, sea-level rise, and climate change.

Blue carbon research across the globe has highlighted considerable spatial heterogeneity in soil organic carbon (SOC) at multiple scales (Atwood et al., 2017; Sanderman et al., 2018). At a regional and global scale, SOC variability has been linked to net primary productivity (Alongi, 2012; Twilley et al., 2017), latitude/climate (Rovai et al., 2018; Twilley et al., 2018; Kauffman et al., 2020), coastal geomorphology (Rovai et al., 2018; Twilley et al., 2018) and Holocene sea-level trends (Rogers et al., 2019). These physical and biological factors and geomorphic evolutionary processes promote and develop unique coastal environmental settings, which ultimately drive macroscale variation in SOC (Rovai et al., 2018). The site-specific variability in SOC is largely attributed to differences in species composition (Ren et al., 2008), stand age (Lovelock et al., 2010; Donato et al., 2011), sources of allochthonous particles (Bouillon and Boschker, 2006; Yang et al., 2014), soil physical and chemical properties (Freeman et al., 2004; Kristensen et al., 2008; Banerjee et al., 2018), elevation and tidal regimes (Liu and Lee, 2006; Spivak et al., 2019), plant-litter biochemistry (Kristensen et al., 2008; Brodersen et al., 2019) and plant-microbe interactions (Fontaine et al., 2007; Alongi, 2014). Several soils and environmental characteristics such as pH, salinity, organic matter, precipitation and tidal inundation influence the mangrove productivity and can also directly or indirectly influence SOC (Yando et al., 2016). Therefore, careful consideration of relevant factors is vital for reliable estimation of SOC at a particular spatial scale.

The Sundarbans is the largest contiguous mangrove forest in the world and is situated in the lower delta plain of the Ganges-Brahmaputra-Meghna (GBM) delta, and stretches across political boundaries between Bangladesh and India (Giri et al., 2011; Sarker et al., 2016). It is either mostly excluded from the global estimates of mangrove SOC (Table 1), or is underrepresented due to a limited number of samples or perceived poor data quality (Donato et al., 2011; Jardine and Siikamäki, 2014; Atwood et al., 2017; Sanderman et al., 2018; Twilley et al., 2018; Kauffman et al., 2020). A range of studies into SOC content in mangrove soils of the Sundarbans have been carried out (Table 1), but these all have limitations. The first comprehensive carbon inventory throughout the Sundarbans was completed by the

Bangladesh Forest Department (BFD) in 2009-10; however, the wider vertical sample depth might have an effect on the SOC estimation within the top meter (Rahman et al., 2015). Allison et al. (2003) and Donato et al. (2011) investigated soil organic carbon at greater depth (>1 m) in the Bangladesh Sundarbans, however, the number of samples (2 and 6 respectively) was not sufficient to address the variability inside the forests. Studies by Khan and Amin (2019) and Hossain and Bhuiyan (2016) measured SOC from different parts of the Sundarbans, however, the sampling was only performed within the top 15 cm. These all the previous studies of SOC in the Sundarbans have limitations resulting from low spatial sampling intensity and limited analysis of soil depth range. Moreover, some global studies like Rovai et al. (2018) argued that past climate-based estimation overestimated SOC by up to 86% for deltaic settings like the Sundarbans. Therefore, accurate investigation on the spatial variation of soil organic carbon and the identification of major controls for such variation in the Bangladesh Sundarbans is urgently needed.

Increasing salinity in the inundated mangroves stimulate a wide range of biogeochemical reactions- including enhancing sulphate concentrations, cation exchange, ionic and osmotic stress, acidity, and turbidity and at the same time reducing soil redox potential and oxygen levels (Setia et al., 2013; Luo et al., 2019). These soil biogeochemical changes in turn alter sediment characteristics and modify plant and microbe communities, which ultimately affect both the soil organic carbon pool and quality. Increased soil salinity affects organic matter solubility by altering flocculation of different soil particles (Wong et al., 2009; Wong et al., 2010; Rath and Rousk, 2015). The Investigations of tidal wetlands across the world reveals a significant negative relationship between the soil organic carbon pool with salinity (Nyman et al., 1990; Craft, 2007; Więski et al., 2010; Morrissey et al., 2014; Hu et al., 2016). High soil salinity decreases decomposition rates by lowering microbial activities in the soil and lowers autochthonous carbon input by reducing plant productivity leading to lower organic carbon in the soil (Baldwin et al., 2006; Marton et al., 2012; Setia et al., 2013; Liu et al., 2017; Zhao et al., 2017). High salinity in general acts as an inhibitor of carbon mineralisation, however the opposite is also evident in some studies suggesting that a small increase in salinity promotes mineralisation process in the oligohaline zone, while in the mesohaline and polyhaline zones, elevated salinity reduces the mineralisation rate (Luo et al., 2019). Therefore, the impact of salinity on the soil organic carbon pool and quality is not uniform in all wetland settings in the world, rather it depends on the local geomorphology and hydrological characteristics.

The aim of the present study is to estimate soil organic carbon (SOC) in the Bangladesh part of the Sundarbans mangrove forest and to better understand the relationship of SOC with three salinity zones (oligohaline, mesohaline and polyhaline) and major forest types. The study hypothesises that higher salinity zones (polyhaline) would yield a lower organic soil carbon stock as a reflection of lower productive vegetation and altered soil physical and biological processes compared with the lower salinity zone (oligohaline). The relationships between physical, chemical properties and vegetation characteristics with SOC are also investigated to develop dependable predictive models for this forest. The novelty of this study lies in the extensive stratified random sampling from all over Bangladesh Sundarbans combined with vertical investigation of soil depth up to 1m.

2. Material and methods

2.1. Study area

The Sundarbans is the largest single block of mangrove forest in the world and a Ramsar and UNESCO World Heritage site (Fig. 1) (Giri et al., 2011; Sarker et al., 2016). The Bangladesh Sundarbans is situated between 21º30' N and 22º30' N and 89º00' E and 89º55' E. The climate of the Sundarbans is warm, humid, and tropical, where annual precipitation varies from 1474 to 2265 mm and mean annual minimum and maximum temperature is between 29 ºC to 31 ºC (Chowdhury et al., 2016; Sarker et al., 2016). Based on the salinity variation, the Sundarbans naturally divides into three distinct zones based on the soil salinity; i) Oligohaline (LSZ) (<2 dS/m, ii) Mesohaline (2-4 dS/m) and iii) Polyhaline (>4 dS/m) (Siddiqi, 2001; Chanda et al., 2016b). Several studies have identified a relationship between tree species abundance along the east-west salinity gradient (Iftekhar and Saenger, 2008; Aziz and Paul, 2015; Sarker et al., 2016; Sarker et al., 2019a). Although *Excoecaria agallocha* is abundant in all three salinity zones, *Heritiera fomes* (characteristic species in Bangladesh Sundarbans) is dominant in both the oligohaline and mesohaline zones, whereas *Ceriops decandra* is abundant in the polyhaline zone

(Sarker et al., 2019a). Some pioneer species, such as *Avicenna* spp. and *Sonneratia apetala* are also present in the mudflats all over the Sundarbans. A short description of all 23 tree species from 10 families found in this study is presented in Table A.1.

2.2. Geology and soils of the Sundarbans

The Sundarbans mangrove forest lies in the south-western part of the Bengal Basin, one of the most extensive sediment reservoirs in the world composed of unconsolidated Quaternary deposits (Rudra, 2014). The rapid sedimentation followed by the tectonic collision of the Indian plate with the Tibetan plate and the Burmese plate in the Miocene triggered the formation of the Bengal Basin (Alam, 1989). Since the Holocene, the dynamic Ganges-Brahmaputra river system has been discharging sediments from the Sub-Himalaya and is still delivering >1 Gt of sediment to the delta plain of India and Bangladesh (Islam et al., 1999; Syvitski and Milliman, 2007). The Sundarbans is of relatively recent origin (3,000-year B.P.) and this mangrove has developed as a result of both fluvial and tidal forces depositing sediments to the GBM river mouth (Goodbred and Kuehl, 2000; Allison and Kepple, 2001; Rogers et al., 2013). Previously, the Ganges was the main source of sediments in the Sundarbans, however, recent changes have resulted from the merging of the Ganges and Brahmaputra which have now migrated to the eastward, far away from the Sundarbans (Rudra, 2014; Islam, 2016). Together with the eastward migration of the primary GBM delta, the construction of the Farakka barrage in the main Ganges River and earthen embankments surrounding the Sundarbans have reduced freshwater flow, resulting in reduced fluvial sedimentation in the Bangladesh Sundarbans. This geomorphological change, in turn, has led to increased remobilisation of sediments by tidal forces (Rogers et al., 2013; Hale et al., 2019; Bomer et al., 2020b). The changed pattern of freshwater flow has resulted in a salinity gradient increasing from the east to the west of the Sundarbans.

The soil is mainly fine-grained, grey coloured, slightly calcareous, and mostly composed of silts to clayey silts (Allison et al., 2003; Bomer et al., 2020a). The subsurface sediment extends up to 6 m in depth in the landward direction and up to 4 m in depth in the seaward direction (Allison et al., 2003). The median grain size ranges between 16-32 µm reflecting the medium silt range. The average dry bulk density (0.81 g cm^{-3}) is higher in the Sundarbans in comparison to other mangroves in the world (Bomer et al., 2020a). The soil physical and chemical properties are varied from the eastern to the western part of Bangladesh Sundarbans, the eastern part is softer, more fertile and receives more fresh sediments than the western part (Siddiqi, 2001). Soils are mostly neutral to alkaline (pH 6.5-8.0), whereas the polyhaline zone is more alkaline than the oligohaline zone. Soils of the western and southern polyhaline zone are comparatively richer in P, K, Na, Mg, Cl^- and Fe, but lower in soil NH^{4-} and Na than the eastern oligohaline zone (Siddiqi, 2001; Sarker et al., 2016). This pronounced differences in soil nutrients and salinity trigger the diversity of vegetation composition in different parts of the Sundarbans.

2.3. Sediment and tree data collection

In the Bangladesh Sundarbans, permanent sample plots (PSP) were established in 1986 by the ODA (Overseas Development Administration) for monitoring growth, regeneration, and long-term ecological changes (Chaffey et al., 1985). A total of 120 PSPs (20 m × 100 m) were established to assess growth rate, regeneration, stocking, and crop composition based on salinity, forest type and accessibility (Iftekhar and Saenger, 2008; Sarker et al., 2019b) (Fig. 1). In this study, sediment samples were collected from 55 plots, of which 50 plots are from PSPs selected at random, and the remaining five plots are from outside PSPs to represent areas outside PSP. Sampling was undertaken in two phases: In the first phase, three sediment cores of 50 cm depth were taken from 18 PSPs. After laboratory analysis of the samples from the first 18 PSPs, it was decided to extend the sediment sampling depth to 1 m and take two core samples from each plot because of little within-plot variation among the initial 54 core samples. In the second phase, an additional 37 PSPs were sampled with two cores sampled at each plot. Altogether, 126 sediment cores from 55 plots were sampled across the whole of the Bangladesh Sundarbans (Fig. 1).

The location of the cores within a PSP was decided by establishing a random circular plot with a radius of 11.3 m (an area of 400 m^2). Within each plot, a small circular plot was laid with 5m radius and sediment cores were taken from east, west and south side (east and west for two cores) from the centre, which is perpendicular to each other. The cores were taken using an open-faced auger (6 cm diameter), which was further subdivided into four depths (0-10, 10-30, 30-50 and 50-100 cm), following the method of Kauffman and Donato (2012). Sediment sub-samples were taken from the middle of each core section with fixed 2.5 cm length, sealed in plastic and subsequently placed in an icebox to reduce oxidation. The sub-samples were kept below 4 ^{O}C in zip-sealed plastic bags until laboratory processing.

For vegetation data, the Diameter at Breast Height (DBH) and height were measured for all trees within the 11.3 m radius plot. DBH was measured at 1.3 m and height was measured with a Vertex-III hypsometer. For small trees with a DBH <14.5 cm, a smaller circular plot (radius 5m) was nested within the 11.3 m plot. The elevation of each plot was calculated by subtracting the mean tree height of the plot from the Digital Surface Model (DSM) taken from the TanDEM-X 90 m satellite data (Hawker et al., 2019). For major forest types, single-species dominance was determined when the relative composition is >75%, and the remaining forest types are termed as Mixed type.

2.4. Laboratory analysis

2.4.1 Soil physical and chemical properties

For each core sub-samples, samples were freeze-dried and re-weighted to determine the bulk density. Bulk density was calculated by dividing the dry mass of the soil by the volume of the soil. Soil pH and soil salinity (as soil conductivity) were measured from a portion of the homogenised dry soil for each core. Dried soils were diluted with distilled water (1:5 ratio), and subsequently, soil pH was measured using a Jenway 3510 Standard Digital pH Meter and soil salinity by a handheld Jenway 470 Conductivity Meter (Hardie and Doyle, 2012).

2.4.2 Total soil organic carbon (SOC)

To determine the soil organic carbon (SOC) and nitrogen content of the soil, any large stones or twigs were removed from the sample and subsequently homogenised and ground with a ball mill. A few milligrams (~40 mg) of the sediment was then passed through an elemental analyser (Thermo Scientific Flash 2000-NC Soil Analyzer) to derive the total carbon and nitrogen as a percentage. Inorganic carbon content was deducted from the total carbon to get organic carbon percentage, according to Howard et al. (2014). The inorganic carbon content was measured from some random samples across all salinity zones using an Analytik Jena Multi EA (Elemental Analyser) 4000. Soil organic carbon density (gm cm^{-3}) for each sample and total organic carbon content (Mg ha^{-1}) of each depth and core were measured according to Howard et al. (2014).

2.5. Statistical Analysis

All statistical analysis and graphics used R 3.6.1 for Windows (R Core Team, 2019). Total organic carbon (Mg ha^{-1}), organic carbon density (gm cm^{-3}) and bulk density (gm cm^{-3}) among three salinity zones and four depths were compared with two-way analysis of variance (ANOVA) test using the 'car' package (Fox and Weisberg, 2019). In order to compare soil organic carbon among vegetation types, total organic carbon (Mg ha^{-1}) was compared with one-way analysis of variance (ANOVA). The results of ANOVA are summarized in Supplementary Information. To derive the relationship among organic carbon density (g cm^{-3}), bulk density and total nitrogen content, data from all the core subsections ($n = 512$) were used. To examine the relationship among SOC and soil physical and chemical parameters (soil salinity, pH, bulk density, Total N, organic C: N, elevation, latitude and longitude) and vegetation characteristics (species richness, tree density, mean DBH and mean height), stepwise multiple linear regression analysis was undertaken. SOC was considered as the dependant variable, whereas all the selected parameters were independent variables. Correlation analysis and principal component analysis (PCA) were carried out to decrease the number of explanatory variables and to reduce collinearity in the regression model. All the variables were standardised before PCA according to Legendre and Legendre (2012). Eigenvalues greater than one were retained and variables with factor loadings >0.35 were treated as potential explanatory variables for the regression model (Jackson, 1993). In all cases, the data were logarithmic (natural) transformed (if needed) to meet the assumptions of normality and equal variances by using Shapiro Wilk and Levene's tests, respectively and subsequently back-transformed to present graphically. The graphical output of the linear model was generated using the 'ggplot2' package (Wickham, 2016).

3. Results

3.1. Soil organic carbon, salinity zones and soil depth

The average soil organic carbon (SOC) density significantly varied from 0.003 gm cm^{-3} to 0.009 gm cm^{-3} in different salinity zones and soil depths (two-way ANOVA for Ln (SOC density), salinity zones, $F_{2, 500} = 112.3$, $p < 0.001$ and soil depths, $F_{3, 500} = 30.1$, $p < 0.001$) (Fig. 2, Table A.2). Both salinity zone and soil depth had a significant interaction effect on the variability of SOC density in the Sundarbans ($F_{6, 500} = 3.5$, $p < 0.01$) (Table A.1). Significantly higher SOC density was found in the topmost depth followed by the subsequent three depths; however, SOC density in the intermediate depths (between 10-30 cm and 30-50 cm) are not significantly different (Fig. 2b), which indicates the unequal variability of SOC with soil depth. The oligohaline zone comprises higher SOC density (gm cm^{-3}) followed by mesohaline and polyhaline zone indicating higher soil organic carbon in the low salinity areas.

The bulk density (BD) of the soil revealed an opposite trend as significantly higher bulk density was observed in the higher salinity zones and in the 50-100 cm soil depth (two-way ANOVA for Ln (bulk density (gm cm^{-3})), salinity zones, $F_{2, 500} = 22.2$, $p < 0.001$ and soil depth, $F_{3, 500} = 46.2$, $p < 0.001$) (Fig. A.1, Table A.3). Likewise, SOC density, the soil organic carbon storage (SOC) for the different depths was significantly different among the three salinity zones and the four soil depths (two-way ANOVA for Ln (SOC), salinity zones, $F_{2, 500} = 118.9$, $p < 0.001$ and soil depth, $F_{3, 500} = 526.2$, $p < 0.001$) (Fig. 3 & Fig. 4, Table A.4). However, higher amounts of SOC were found in the 50-100 cm depth in comparison to the top three depths (Fig. 4). The top meter SOC ranges from 26.2 Mg ha^{-1} to 107.9 Mg ha^{-1} in the Sundarbans, where oligohaline zone comprises the highest SOC (74.8 Mg ha^{-1}), followed by the mesohaline (59.3 Mg ha^{-1}), and the polyhaline zone (48.3 Mg ha^{-1}) (Table 2).

3.2. Soil organic carbon and forest types

One-way ANOVA revealed that SOC varied with major forest types in the Sundarbans ($F_{7, 47} = 3.3$, $p < 0.01$) (Table A.5). As shown in Fig. 5, the average SOC content in the *Bruguiera* sp. stand was the highest, with an average of 105.3 Mg ha^{-1}, followed by *Sonneratia* sp. and *Avicennia* sp., with an average of 68.7 Mg ha^{-1} and 67.1 Mg ha^{-1}, respectively. The Tukey HSD test showed that the other forest types had no significant effect on SOC content, which ranges from 50.2 Mg ha^{-1} to 67.0 Mg ha^{-1} for *Ceriops* and *Heritiera* forest types, respectively (Table A.6).

3.3. Soil physical, chemical properties and vegetation characteristics

The soil physical, chemical properties and vegetation characteristics vary considerably among the three salinity zones (Table 2). As expected, oligohaline zones had relatively low average soil bulk density, pH, and soil salinity, in comparison to higher salinity zones. Additionally, significantly higher SOC and lower total N contributes higher organic C: N in the oligohaline zone, although it is similar to the mesohaline zone (p <0.05). BD and SOC density showed a statistically significant negative relationship (r = -0.47, p <0.001) (Fig. 6A). However, the soil organic carbon (SOC) density and soil nitrogen density is significantly positively correlated with soil nitrogen density across the Sundarbans (r = 0.66, p <0.001) (Fig. 6B). Analysis from the satellite and tree height data reveals that the average elevation is higher in the polyhaline zone. The average DBH and height of the trees were statistically significantly higher in both the oligohaline and mesohaline zone, whereas the average stem density was higher in both the mesohaline and polyhaline zone (p <0.05). Bivariate relationship between SOC and other soil physical, chemical properties and vegetation characteristics are presented in the supplementary Fig. A.2.

3.4. Relationship of SOC with soil and vegetation properties

SOC content was positively correlated with tree DBH, tree height, organic C: N, latitude, and longitude, but negatively correlated with soil salinity, bulk density, soil pH, tree density and elevation (p < 0.05) (Fig. 7). As total nitrogen and species richness did not show any significant correlation with SOC content, these two parameters were discarded from the subsequent PCA analysis. The measured properties also showed a significant positive and negative correlation among themselves, which indicates a source of multicollinearity, a phenomenon which makes multiple regression unreliable. Therefore, principal component analysis was used to identify and group those properties that influence SOC the most and to overcome the influence of multicollinearity.

Principal component analysis (PCA) was performed with ten variables to assemble and isolate the smallest possible of subsets to explain the variation of the dataset (Fig. 8). The PCA result indicates that the first two principal components explained more than two-thirds of the total variation with an eigenvalue greater than 1. The most important component (PC1) explained 49.5% with the highest loadings (>0.35) for soil SS (soil salinity) and pH. On the other hand, the second component showed higher leadings for tree H, DBH and soil C: N with 20% explained variation (Table A.7). As soil SS and pH are highly correlated with each other (r = 0.76, $p < 0.05$) (Fig. 7), the variable with the highest loading, soil SS, was selected from the first component for the regression model. Similarly, tree H was discarded due to collinearity with tree DBH and therefore, tree DBH and soil C: N was selected from the second component.

By using the PCA-derived subset of variables, the relationship between SOC and soil and vegetation properties was obtained by using stepwise multiple linear regression (MLR). The regression results showed that soil salinity alone could explain 50% SOC variability in the Sundarbans, however, the percentage increases to 57% and 62% when soil C: N or soil C: N and tree DBH are added to the model (Table 3). Although all three regression models are highly significant (Table A.8), the best subset of MLR model was selected based on the largest adjusted R^2 value and the smallest Mallow's Cp, AIC (Akaike Information Criteria) and RMSE (Root Mean Squared Error) and presented in Eq.1.

$$\mathrm{Ln}\ (SOC) = 3.439 - 0.077\ SS + 0.274\ \mathrm{Ln}\ (\mathrm{C{:}\ N}) + 0.017\ \mathrm{DBH} \ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 1}$$

4. Discussion

The reported average soil organic carbon (SOC) density in this study is lower than previous estimates from the Sundarbans and far lower than average estimates of SOC density from global mangroves (Table 1). SOC density, the standardized carbon stock measurement with depth, is the most useful parameter to compare SOC between different forests (Donato et al., 2011; Weiss et al., 2016). However, due to unreported bulk density, it was not possible to convert from the reported organic carbon (%) to SOC density for most of the local and world studies. Despite a greater range of soil organic carbon (SOC) percentage in this study (0.3 – 4.4%), the average value (1.2 %) is in line with most previous studies, although higher than estimates published by Ray et al. (2011), Banerjee et al. (2012), and Allison et al. (2003). These differences are likely to be attributed to variable sampling strategies along with variable soil depth or different methods used for carbon estimation. Likewise SOC density, the average top 1m SOC storage in the Bangladesh Sundarbans (50.9 ± 15.2 Mg ha^{-1}) is almost half of the previous estimate by Rahman et al. (2015), Sanderman et al. (2018) and Atwood et al. (2017). Estimates of soil organic carbon could fluctuate based on the differences in sampling design, choice of analytical method and soil depth (Howard et al., 2014; Nayak et al., 2019). In the case of mangroves, Passos et al. (2016) found overestimation of organic carbon measured with the oxidation method in comparison to the elemental analyser. Anaerobic microbial decomposition yields reduced soil compounds (i.e., Fe^{2+}, S^{2-}, Mn^{2+}, and Cl^{-}) in mangroves, which might interfere with organic carbon determination with chemical oxidation method (Nelson and Sommers, 1996; Bisutti et al., 2004; De Vos et al., 2007; Nóbrega et al., 2015). Apart from using different methods, the SOC variation originates from the consideration of soil depth in sample design as the SOC concentration is a function of soil depth and shows considerable variability (Wuest, 2009; Kauffman and Donato, 2012; Jandl et al., 2014). Moreover, using coring for sampling might have an influence on soil bulk density estimation leading to lower SOC stock estimation in deeper soils (Rau et al., 2011; Gross and Harrison, 2018).

In comparison to global studies, the estimated top 1m SOC stock is lower in the Sundarbans than the reported average from sites distributed all over the world (Table 1). Based on model-based georeferenced database of mangrove SOC, the global SOC map showed that the Sundarbans contains the lowest SOC stocks per ha in the world (Sanderman et al., 2018). Compared to direct estimates from 190 sites across the world by Kauffman et al. (2020), the Sundarbans contains higher SOC than only two other mangrove forests, the Porto Céu mangrove in Brazil (48 Mg ha^{-1}) and the Bu Tinah Janoub in the United Arab Emirates (33 Mg ha^{-1}), located in lower and higher latitudes respectively than the Sundarbans. However, global comparison in soil carbon among tropical, subtropical and temperate mangroves showed a contrasting relationship with latitudes (Atwood et al., 2017; Twilley et al., 2018; Kauffman et al., 2020; Ouyang and Lee, 2020). Both Kauffman et al. (2020) and Ouyang and Lee (2020) found significantly lower soil carbon in mangroves >20 ºN, although the former study had fewer samples largely limited to the middle east hyper arid mangroves. On the other hand, Atwood et al. (2017) and Twilley et al. (2018) documented the poor relationship between latitude and SOC stocks. This poor relationship might be attributed due to the poor representation of samples in the studies from the subtropical mangroves like the Sundarbans.

The low soil carbon in the Sundarbans is largely due to high mineral sediment deposition (Sanderman et al., 2018; Twilley et al., 2018), low burial rate (Ray et al., 2011), rapid turnover rate (Ray et al., 2018), historical logging, stand age (Marchand, 2017), plant litter quality (Rovai et al., 2018) and biological processes. Being both a tide and river-dominated ecosystem, the carbon allocation in the above and below ground is very complex, largely dependent on the local and regional geomorphic and geophysical drivers (Twilley et al., 2018). In riverine deltas, trees invest much of the carbon to the above ground to keep pace with sedimentation and sea-level rise, which is evident in the oligohaline zone with greater forest productivity (Twilley et al., 2018; Sarker et al., 2019a; Sarker et al., 2019b). Moreover, research has highlighted that mangroves subjected to frequent cyclones leading to temporary losses of above ground carbon are usually followed by rapid below ground carbon gains during recovery process according to the 'Ecosystem Development' theory (Odum, 1969; Danielson et al., 2017; Kominoski et al., 2018). These rapid carbon gains in the above ground and the disturbance from the catastrophic cyclones could be the source of higher autochthonous input to the below ground. Nonetheless, higher tidal amplitude in the Sundarbans leads to higher carbon export totalling 7.3 Tg C yr^{-1} to the adjacent Bay of Bengal, which is higher than any other mangroves in the world (Ray et al., 2018). This rapid carbon turnover results in reduced burial of organic matter (0.18%) in the soil (Ray et al., 2011). Moreover, the pronounced tidal cycles in the Sundarbans affects carbon burial process by altering soil water chemistry (Chatterjee et al., 2013; Spivak et al., 2019). Besides high carbon turnover rate, the Sundarbans is believed to have become tidally active in the recent past due to reduced freshwater flow from the Ganges-Brahmaputra-Meghna river (Rogers et al., 2013; Hale et al., 2019). However, despite the historical reduction of sedimentation, the Sundarbans is itself still keeping pace with sea-level rise with the highest average surface elevation and vertical accretion rate (0.74 and 2.71 cm yr^{-1}) compared to the worldwide average (Bomer et al., 2020a; Bomer et al., 2020b). This high sedimentation rate is the outcome of the massive flux of clastic sediments which attenuates the amount of organic carbon per unit area.

The century-long historical exploitation in the Sundarbans before the felling moratorium in 1989 has largely decreased the populations of threatened tree species (Siddiqi, 2001; Sarker et al., 2011). This in turn is likely to have lessened the continuous autochthonous input of organic matter in the forest and reduced the overall stand age. Studies also showed that historical harvesting had altered the species composition in the Sundarbans, with decreasing abundances of *Heritiera fomes*, *Ceriops decandra* and *Xylocarpus mekongensis* and increasing for *Excoecaria agallocha* (Sarker et al., 2016). The SOC stock also depends on the age of the stands as evident in the Chrono sequence study on SOC stocks in French Guiana which revealed that the SOC varied from 4 to 107 Mg ha^{-1} from young stand to senescent stage (Marchand, 2017). In addition, studies have suggested that lower organic carbon in the soil is mostly associated with higher C: N of the plant litter which has resulted from lowering decomposition speed and decreasing carbon-use efficiency of the decomposer (Bouillon et al., 2003; Zhou et al., 2019). Compared to mangrove associates, the senescent leaves of true mangroves contain considerably higher C: N (~33) in the Indian part of Sundarbans (Chanda et al., 2016a). Kamruzzaman et al. (2019) observed a decreasing trend of C: N of the leaf litter in both forest floor and buried condition starting from 40, but barely reached below 30 after 196 days of decomposition study, suggesting N limitation in the oligohaline zone of the Bangladesh Sundarbans. The low organic carbon can also be attributed by the abundance of leaf-consuming organisms ingesting organic litter detritus both at surface and subsurface in burrows. The Sundarbans encompasses a wide range of gastropod species (e.g., *Cerithedia cingulata*, *Cymia lacera*) that predominantly consume mangrove detritus (Nayak et al., 2014).

Variation in SOC stocks among different forest types is often mediated by the primary productivity, resources allocation in different parts (e.g. above and below ground) and microorganism activity is driven by a number of biological (e.g. bioturbation and species composition) and physical (e.g. soil texture, salinity, inundation and nutrients) factors (McLeod et al., 2011). Therefore, differing stand structure and composition of mangrove forests in different tidal regimes yield variable SOC stock (Lacerda et al., 1995; Gleason and Ewel, 2002). Moreover, the long and short-term resilience and resistance of microbial communities are largely dependent on the structure and zonation of mangrove communities reflecting environmental gradients (Capdeville et al., 2019). In this study, the species with higher SOC stock such as *Bruguiera* sp., *Sonneratia* sp. and *Avicennia* sp. are frequently inundated due to proximity to the river and low land than other species in the Sundarbans (Siddiqi, 2001; Sarker et al., 2016). These high inundation regimes, in turn, lead to increased microbial activity and a higher level of dissolved organic carbon in the sediment (Wang et al., 2013; Chambers et al., 2014; Chambers et al., 2016). Regular tides also bring sediments along with high allochthonous input whereas the raised less-inundated areas foster autochthonous SOC and less microbial activity (Lovelock et al., 2015; Woodroffe et al., 2016). Rao et al. (1994) found almost double C: N ratio in fresh leaves of *Bruguiera* sp. compared with other mangrove species, suggesting higher input of autochthonous carbon. Being the pioneer species in the succession of the Sundarbans, both *Sonneratia* sp. and *Avicennia* sp. are resilient to disturbances leading to higher SOC than climax and seral species (Table A.1) and accumulate a large quantity of organic litter in the tidal channel close to the river or seafront (Sarker et al., 2016; Bomer et al., 2020a). The variability of SOC stocks among forest types followed a similar pattern to the global studies by Atwood et al. (2017), except for *Sonneratia* sp. which was found to hold less SOC stock than *Heritiera* and *Ceriops*. On the other hand, Kauffman et al. (2020) found significantly lower below ground carbon stocks in *Avicennia* sp., especially in the arid mangroves of Middle-East Asia, which is solely occupied by this species. Therefore, the impact of above ground vegetation of below ground is largely site-specific, and it depends on a wide range of factors.

The unexplained variation of the best multiple regression models (R^2 = 0.64) highlights the necessity of including other soil and environmental parameters such as soil cations and anions, clay characteristics and texture, precipitation, temperature, and river discharge. This study did not address these properties and suggests future studies incorporate a wider range of parameters to gain a better understating of organic carbon dynamics in the Sundarbans. In particular, for better ecosystem management, future research should include information relating to contextualising soil (e.g. soil texture, grain size and minerology), biogeochemical (e.g. important properties of soil and pore-water chemistry such as sulphate, oxygen, nitrate, ferric oxides in case of mangroves) and ecological (e.g. vegetation and plat-microbe interaction) properties (Luo et al., 2019; Spivak et al., 2019). However, soil salinity is considered as the outcome of the combined impact of these climatic and environmental variables in the Sundarbans resulting pronounced differences of SOC stock among the three salinity zones (Sarker et al., 2016; Sarker et al., 2019b; Rahman et al., 2020). Several previous studies have confirmed that salinity determines the strong zonation of tree species and diversity in the Sundarbans, which in turn leads to comparatively higher diversity and taller tree species in the oligohaline followed by mesohaline and polyhaline zone (Aziz and Paul, 2015; Sarker et al., 2016; Sarker et al., 2019a; Sarker et al., 2019b; Rahman et al., 2020). Comparatively higher productive trees (e.g. higher DBH and higher height) promotes organic matter accumulation through producing higher litter mass and increases SOC stock by forming stable aggregates from roots and pneumatophores (Lange et al., 2015). The three salinity zones also comprise differential soil physical, chemical properties and vegetation characteristics that usually affects SOC storage by influencing microbial decomposition, soil water chemistry, plant-microbe interaction, and plant litter quality. While comparing nutrient concentration in the leaf litter of *Sonneratia apetala*, one of the major pioneer species in the Sundarbans, Nasrin et al. (2019) found lowest concentrations of N, P and K and the highest concentrations of Na in the polyhaline zone, reflecting higher C: N in the leaf litter. However, the low SOC in the polyhaline zone is also coincided with the low C: N indicting inwelling of marine and terrestrial suspended particulate materials (Bouillon et al., 2003). The strong positive correlation ($r = 0.66$, $p < 0.001$) between carbon and nitrogen density indicates that the source of carbon and nitrogen is likely to be same and can vary spatially (Matsui et al., 2015).

Although the Sundarbans is considered to be of recent origin, the large accommodation space exists due to accretion and erosion with historical relative sea-level variability (Goodbred and Kuehl, 2000; Tyagi and Sen, 2019). Therefore, the Sundarbans might have a 3m organic layer in the seaward direction and much more in the landward (Allison et al., 2003). By considering this vertical depth and the area covered by mangrove forest, the Sundarbans are likely to contain considerable volumes of soil organic carbon. Previous research has demonstrated that mangroves holding higher carbon storage also have a higher rate of deforestation with 50 % mangrove loss attributed to Indonesia, which holds about 25% of soil carbon in the world’s mangroves; the figure increases to 75% when Malaysia and Myanmar are considered (Atwood et al., 2017). Therefore, mangroves from these countries are considered as a significant source of emissions due to high deforestation and forest conversion (Hamilton and Friess, 2018). On the other hand, in Bangladesh, despite the lower SOC stock in the Sundarbans mangrove forest demonstrated by this paper, recent positive trends in forest cover demonstrate the value of blue carbon conservation and an improved understanding of carbon storage will be of benefit to the inclusion of mangroves in national and international climate strategies and policies.

5. Conclusion

The top meter of soil organic carbon (SOC) per area in the Bangladesh Sundarbans is lower than has previously been reported. However, the total SOC will likely to be greater if total vertical depth is considered. The soil organic carbon stock (SOC) in the Sundarbans is largely influenced by soil salinity, probably by amending the forest productivity and microbial activity. The results highlighted that increasing salinity as result of predicted sea-level rise will likely have pronounced effects on future soil carbon accumulation rates by altering the soil environment and vegetation characteristics. The study underlines the importance of spatial conservation planning measures and initiatives to conserve and maximize carbon accumulation and to contribute to global climate change adaptation and mitigation strategies. Results suggest that high sediment carbon zone in the eastern part of the Sundarbans is highly vulnerable to tourism and economic development activities. In terms of climate change mitigation and adaptation, the conservation of the existing carbon stock should receive much higher priority rather than the debates of high-low carbon stock. The Bangladesh Sundarbans can act as an important blue carbon hotspot due to the high sedimentation and carbon sequestration rate and conservation priority by the government. However, disturbances such as sea-level rise, global warming, eutrophication, and landscape development might hinder this conservation activities in the future.

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Conflict of interest

The authors agreed that they have no conflict of interest.

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Fig. 1. Sundarbans mangrove forest, Bangladesh. Legend colour represents three major salinity zones (Chanda et al., 2016b). ESRI Basemap Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community.

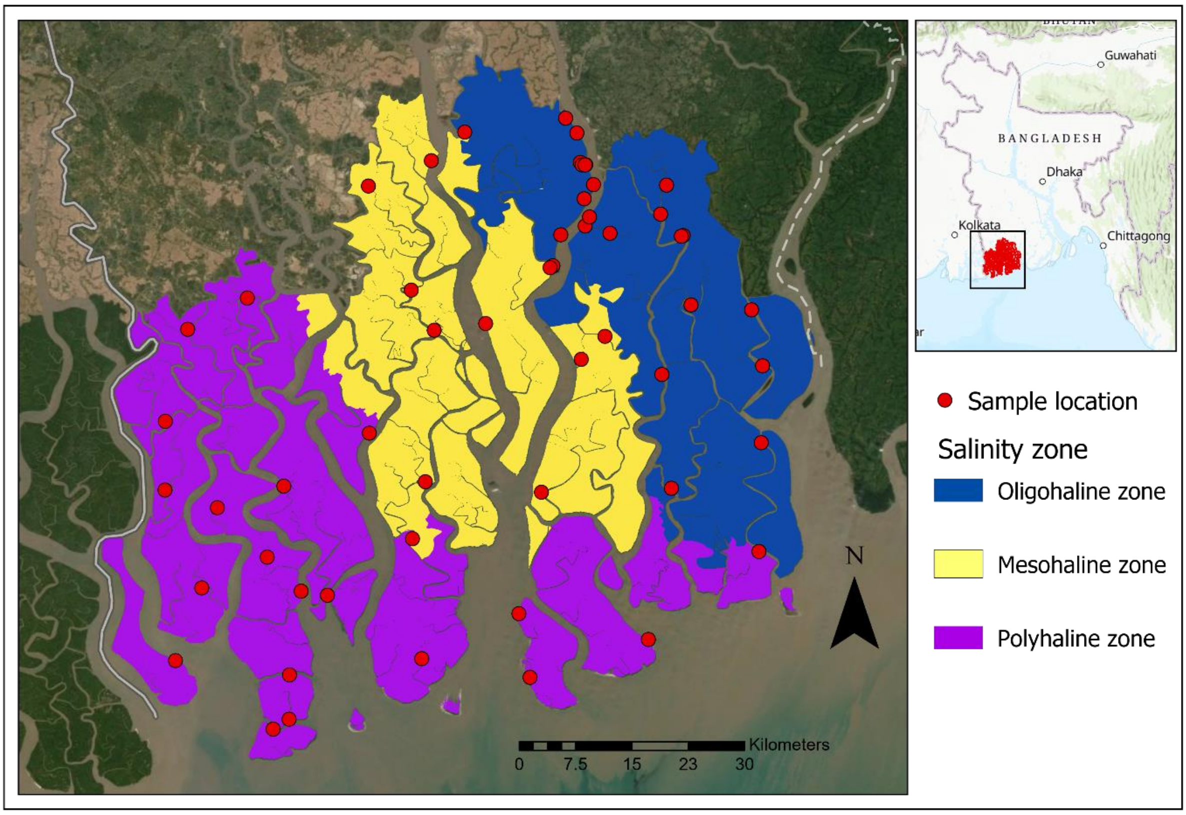

Fig. 2. (A) The distribution of soil organic carbon (SOC) density (gm cm^{-3}) in four soil depths presented as violin-box plot, where the black vertical line represents the median and black dots are outliers. Here, the width of violin plot represents the proportion of the data located there as a measure of kernel probability density. (B) Average SOC density (gm cm^{-3}) in three salinity zones and four soil depths.

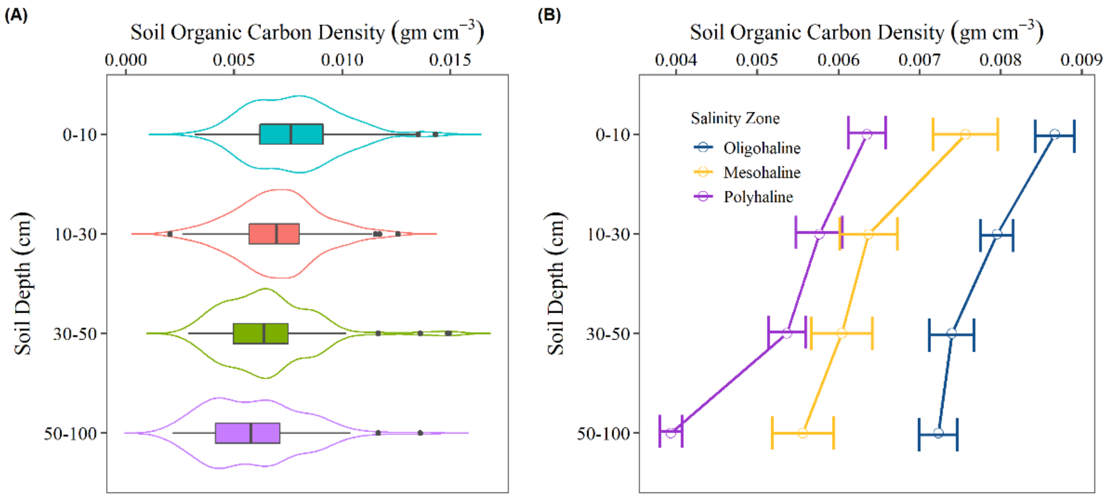

Fig. 3. Spatial distribution of total soil organic carbon (SOC) (Mg ha^{-1}) and soil salinity (dS/cm) in the Sundarbans. Note that circle represents the amount of SOC and gradual colour ramp reveals soil salinity indicating green to red as from low to high salinity. Three major salinity zones are represented according to Chanda et al., (2016b).

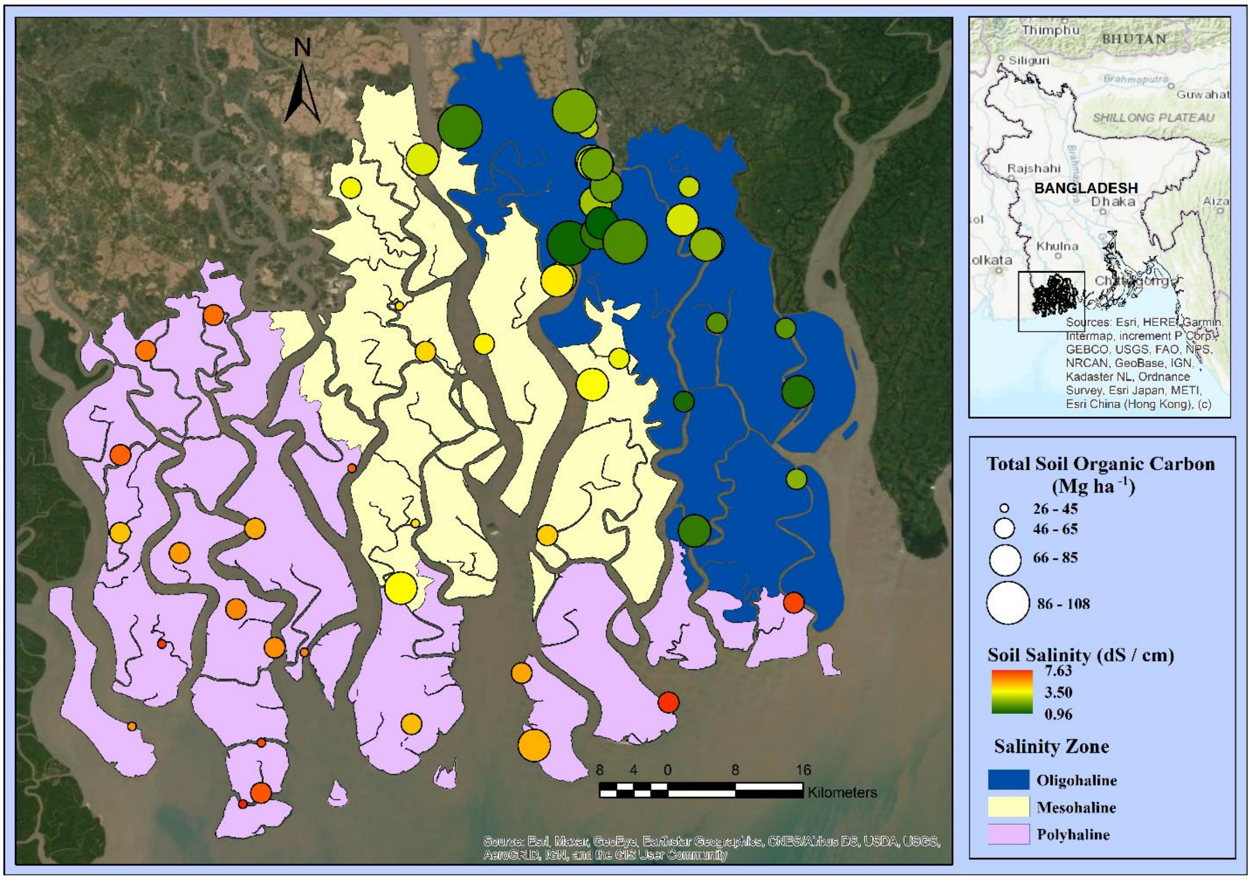

Fig. 4. Average soil organic carbon (Mg ha^{-1}) in different soil depths in three salinity zones.

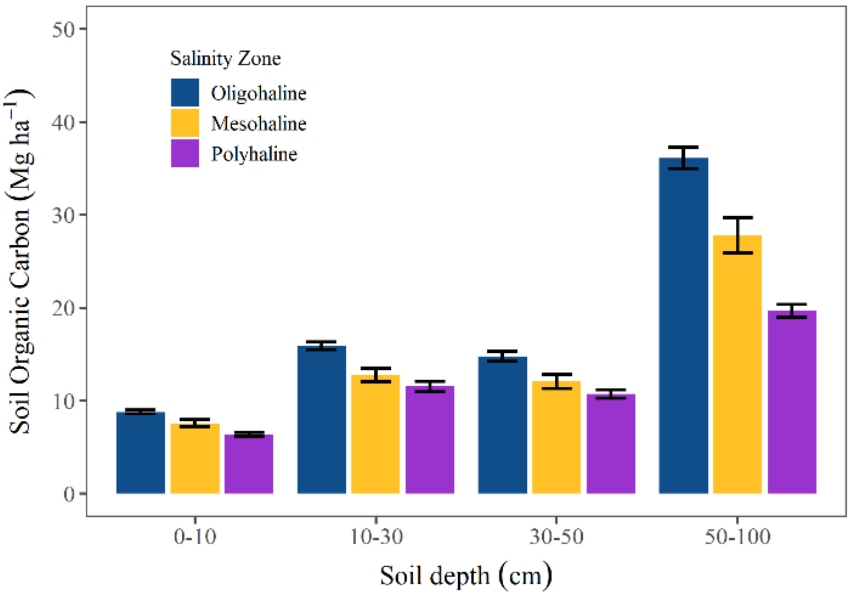

Fig. 5. Integrated violin-box plot shows average soil organic carbon (SOC) in major forest types in the Sundarbans. The black vertical line of box plot represents the median and the width of violin plot represents the proportion of the data located there as a measure of kernel probability density.

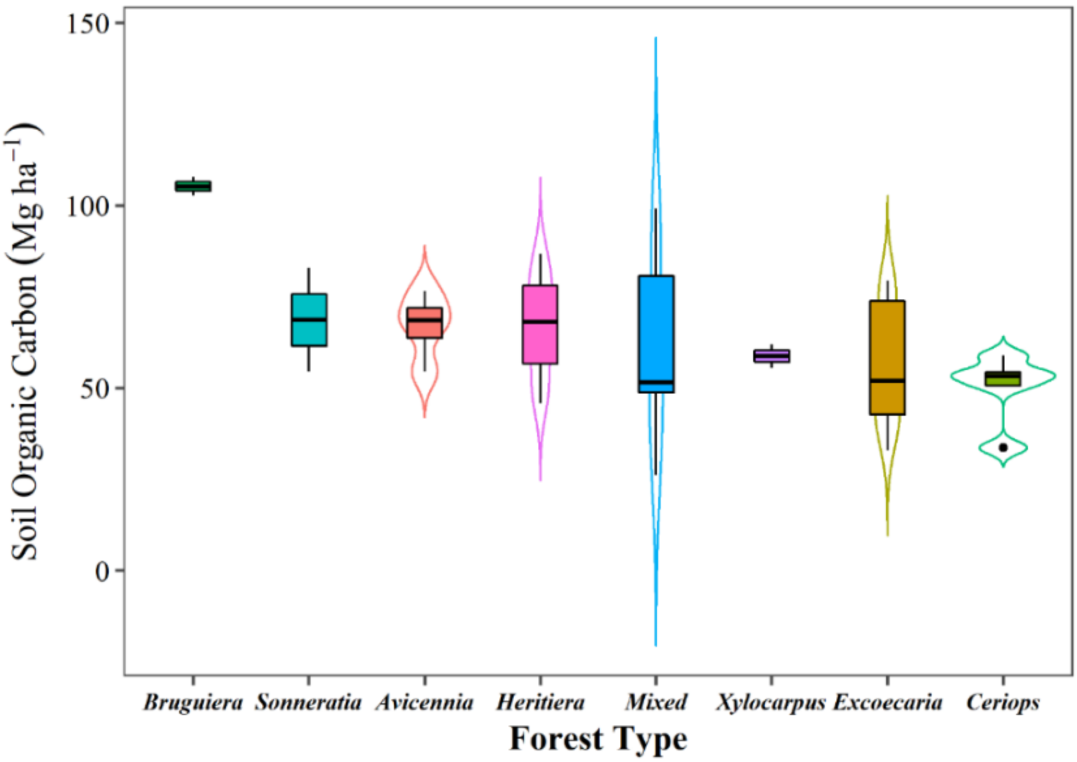

Fig. 6. (A) Relationship between bulk density and soil organic carbon density. (B) Relationship between soil nitrogen density and soil organic carbon density.

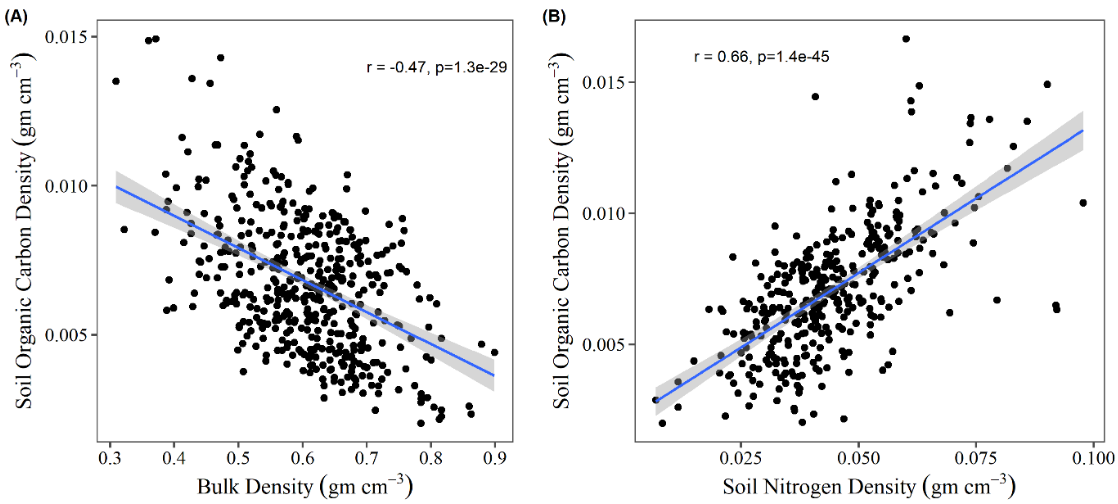

Fig. 7. Correlation matrix among SOC and other physicochemical, geophysical and vegetation properties. The number of each block shows the Spearman's rank correlation coefficients at $p < 0.05$, where red and violet colour represents respective positive and negative correlations. The white block indicates the correlation coefficient is statistically insignificant. The soil properties: SOC = Soil organic carbon, SS= soil salinity, BD = Bulk density, pH= soil pH, TN = Total Nitrogen, C: N = organic C- total Nitrogen ratio, the vegetation characteristics: SR = Species richness, TD = Tree density, DBH = mean Diameter at Breast Height, H= Mean height and geophysical properties: E= Elevation, LAT = Latitude and LONG= Longitude.

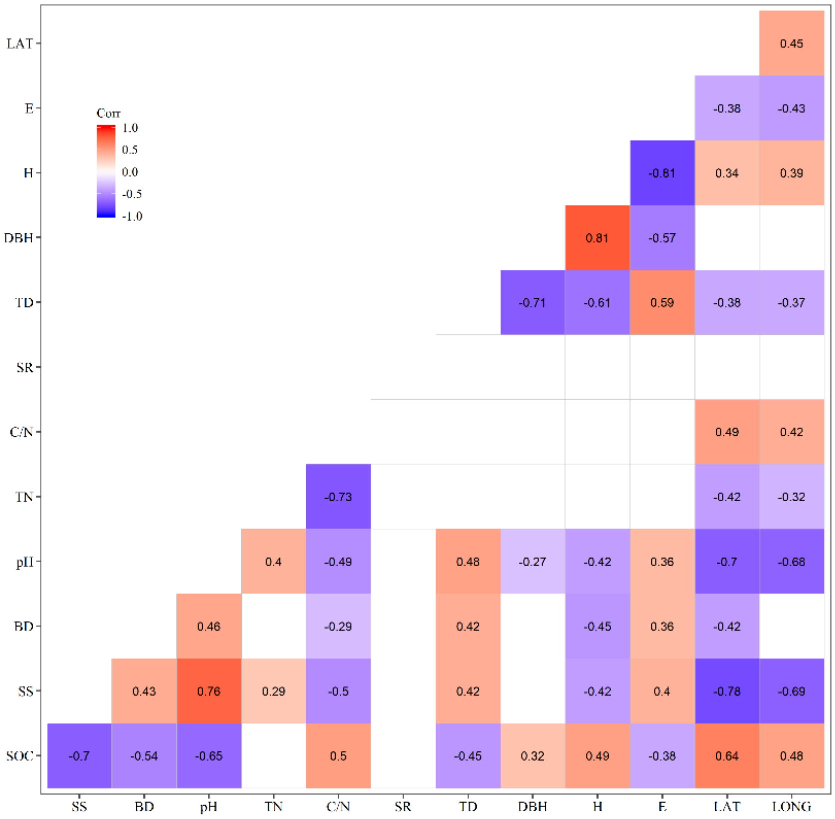

Fig. 8. Principal component analysis (PCA) biplot of soil physicochemical, geophysical and vegetation characteristics as vectors (n = 10) and mangroves areas are coloured coded as three salinity zones (n = 55). The soil physicochemical properties included SS= soil salinity, pH= soil pH, BD = Bulk density, C: N = organic C- total Nitrogen ratio, geophysical properties comprised LAT = Latitude, LONG= Longitude, E= Elevation, and the vegetation characteristics included TD = Tree density, DBH = mean Diameter at Breast Height, H= Mean height. Here, perpendicular direction signifies uncorrelated relationship, while negative and positive correlated vectors are presented in the opposite vectors and small angle vectors, respectively.

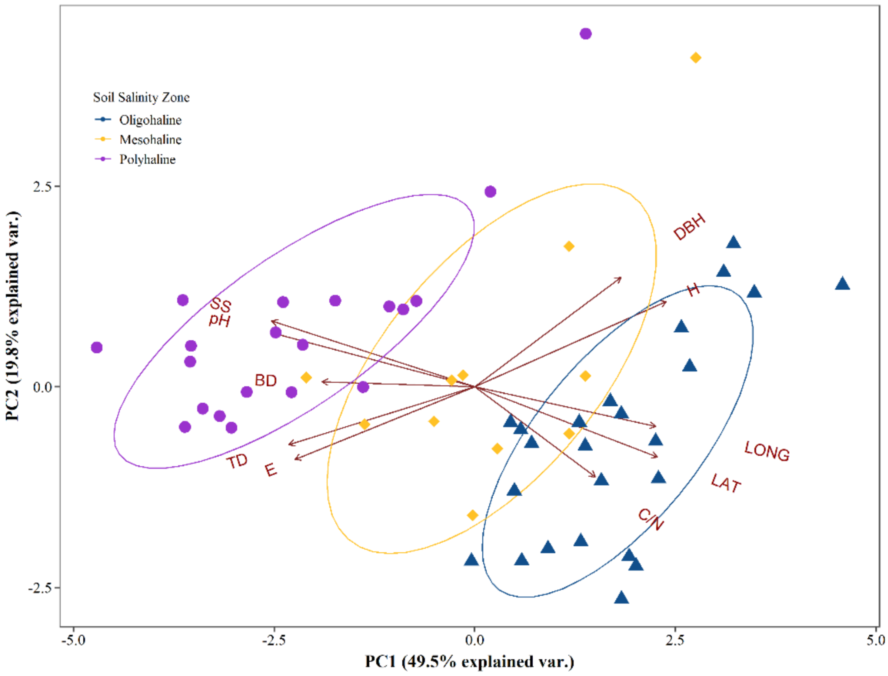

Table 1. Comparison of Soil Organic Carbon (SOC) density and stock among studies in the Sundarbans and globally.

Study area		Study	Sample size	Depth (cm)	Methods	Mean Soil organic carbon percentage (%) (range)	Mean Soil organic carbon density (gm/cm^3) (range)	Mean top m Soil Organic Carbon Storage (Mg/ha) (range)
Sundarbans	Bangladesh	Bomer et al. (2020a)	56	100 cm	Coring, CHN analyser	0.9 (0.6-1.5)	0.010 (0.008-0.011)	-
		Khan and Amin (2019)	35	15 cm (0-15)	Coring, wet oxidation	0.6 (0.4 – 1.0)	-	-
		Sanderman et al. (2018)	-	100 cm	Literature and Model based	-	-	127 (74- 463)
		Atwood et al. (2017)	-	100 cm	Literature and Model based	-	-	118
		Prasad et al. (2017)	400	100 cm (1 cm interval)	Coring, CN analyser	1.25 (0.8 – 2.4)	-	-
		Hossain and Bhuiyan (2016)	96	5 cm (0-5)	Coring, wet oxidation	1.2 (0.6 – 2.0)	-	-
		Rahman et al. (2015)	150	100 cm (0-30, 30-100)	Coring, wet oxidation	-	0.011 (0.007 – 0.014)	112 (90 - 134)
		Donato et al., (2011)	4	100 cm (0-30, 30-100)	Coring, wet oxidation	1.7 (1.6-1.7)	0.016 (0.015–0.016)	-
		Allison et al. (2003)	4	600 cm (0-600)	Coring, CHN analyser	0.5 -1.1	-	-
	India	Dutta et al. (2019)	48	40 cm (0-10, 10-20, 20-30, 30-40)	Coring, wet oxidation	1.25 (0.8-1.6)	-	-
		Prasad et al. (2017)	300	100 cm (1 cm interval)	Coring, CN analyser	0.8-5.2	-	-
		Dutta et al. (2013)	15	25 cm (0-5, 5-10, 10-15,15-20, 20-25)	Coring, TOC analyser	1.8 (1.2 - 2.1)	0.017 (0.013 – 0.019)	-
		Banerjee et al. (2012)	140	40 cm (0-10, 10-20, 20-30, 30-40)	Coring, wet oxidation	1.0 (0.5 – 1.4)	0.011 (0.007 – 0.015)	-
		Mitra et al. (2012)	120	40 cm (0-10, 10-20, 20-30, 30-40) cm	Coring, wet oxidation	0.7 (0.4 – 1.1)	0.009 (0.006 – 0.012)	-
		Ray et al. (2011)	16	30 cm (0-30)	Coring, wet oxidation	0.6 (0.5-0.7)	-	-
Global studies		Kauffman et al. (2020)	190 sample plot data from 5 continents in different soil depth			-	-	334 (33 – 789)
		Sanderman et al. (2018)	Model based estimation of carbon from literature values of 1812 samples			-	-	361 (94-628)
		Rovai et al. (2018)	Model based estimation of carbon from literature values of 932 samples			-	0.033 (0.001 – 0.153)	-
		Atwood et al. (2017)	Literature based estimation from 1230 sampling locations			-	-	283 (15 – 1527)
		IPCC (2014)	Literature based estimation			-	-	428
		Jardine and Siikamäki (2014)	Model based estimation of carbon from literature values of 932 samples			5.7 (0.1 – 43.3)	0.032 (0.014 – 0.115)	369 (272 – 703)
		Donato et al. (2011)	Field based data from Indo-pacific area of 25 samples			11.9 (1.7 -21.5)	0.043 (0.016 – 0.076)	-

Table 2. Overview of measured soil parameters and vegetation characteristics. Values are presented as mean (± SD), where n ≥ 3. Lowercase letters indicate significant variability among salinity zones, according to least-significant difference (LSD) test at α = 0.05.

Salinity zone	**Bulk density (gm cm^{-3})**	**Soil pH**	**Soil salinity (EC dS/cm)**	**Total Soil Organic Carbon (Mg ha^{-1})**	**Total Nitrogen (Mg ha^{-1})**	**Organic C: N**	**Elevation (m)**	**Stem Density (ha^{-1})**	**Height (m)**	**DBH (Diameter at Breast Height) (cm)**
Oligohaline	0.58 (0.07) ^{b}	7.06 (0.26) ^{c}	1.49 (0.32) ^{c}	74.77 (14.93) ^{a}	2.66 (1.19) ^{b}	21.30 (7.23) ^{a}	3.39 (1.78) ^{b}	5,009 (2,485) ^{b}	7.98 (2.03) ^{a}	8.12 (2.41) ^{a}
Mesohaline	0.62 (0.04) ^{ab}	7.43 (0.19) ^{b}	3.07 (0.56) ^{b}	59.30 (15.80) ^{b}	3.52 (1.08) ^{a}	17.30 (6.87) ^{a}	3.67 (1.01) ^{ab}	6,876 (3,290) ^{ab}	7.88 (2.63) ^{a}	8.60 (5.36) ^{ab}
Polyhaline	0.63 (0.05) ^{a}	7.80 (0.26) ^{a}	5.56 (0.85) ^{a}	48.25 (10.32) ^{c}	3.81 (0.98) ^{a}	13.08 (3.00) ^{b}	4.79 (1.52) ^{a}	8,750 (4,798) ^{a}	5.98 (1.66) ^{b}	6.72 (4.12) ^{b}

Table 3. Summary statistics of regression model. Here, SS = Soil salinity, C: N = Soil organic carbon: Nitrogen and DBH= tree Diameter at breast height.

Model	R^2	**Adjusted** R^2	**C(p)**	**AIC**	**RMSE**
1. SS	0.508	0.498	18.217	-10.457	0.212
2. SS and C: N	0.590	0.574	8.650	-18.513	0.196
3. SS, C: N and DBH	0.637	0.616	4.00	-23.255	0.186

Table A.1. List of tree species found in the Sundarbans with taxonomy, distribution in salinity zones, inundation condition and succession stage.

Latin name	Local name	Family	Salinity zone	Inundation condition	Succession stage
***Aegiceras corniculatum* (L.) Blanco**	Kholshi	*Primulaceae*	M, P	WL, WH	S
***Aglaia cucullata* (Roxb.) Pellegr. ***	Amoor	*Meliace*	O	WH	S
***Avicennia alba* Blume.**	Sada Baen	*Avicenniaceae*	P	WL	Pr
***Avicennia marina* (Forssk.) Vierh.**	Moricha Baen	*Avicenniaceae*	P	WL	Pr
Avicennia officinalis L.	Kala Baen	*Avicenniaceae*	O, M, P	WL	Pr
***Bruguiera gymnorrhiza* (L.) Lam.**	Lal Kakra	*Rhizophoraceae*	O, M, P	WL	S, C
***Bruguiera sexangula* (Lour.) Poir.**	Holud Kakra	*Rhizophoraceae*	O, M, P	WL	S, C
***Cerbera manghas* L. ***	Dakur	*Apocynaceae*	O	WO	S
***Ceriops decandra* (Griff.) Ding Hou**	Goran	*Rhizophoraceae*	O, M, P	WO	C
***Cynometra ramiflora* L. ***	Singra	*Fabaceae*	O	WH	S
***Excoecaria agallocha* L.**	Gewa	*Euphorbiaceae*	O, M, P	WH, WO	S
***Excoecaria indica* (Willd.) Muell. Arg. ***	Batul	*Euphorbiaceae*	O	WH	S
***Heritiera fomes* Buch. -Ham.**	Sundri	*Malvaceae*	O, M, P	WO	C
***Hibiscus tiliaceus* L. ***	Bola	*Malvaceae*	O, M	WH	S
***Intsia bijuga* (Colebr.) Kuntze ***	Bhaila	*Fabaceae*	O, M	WH	S
***Kandelia candel* (L.) Druce**	Vatkathi	*Rhizophoraceae*	M, P	WL	S
***Lumnitzera racemosa* Willd.**	Kirpa	*Combretaceae*	P	WH, WO	S
Millettia pinnata* (L.) Panigrahi	Karanj	*Fabaceae*	O	WL	S
***Rhizophora apiculata* Blume.**	Bhora Jhana	*Rhizophoraceae*	M, P	WL	S
***Rhizophora mucronata* Lamk.**	Jhana Garjan	*Rhizophoraceae*	M, P	WL	S
***Sonneratia apetala* Buch. -Ham.**	Keora	*Lythraceae*	O, M, P	WL	Pr
***Xylocarpus granatum* K.D. Koen.**	Dhundul	*Meliaceae*	M, P	WH	S
***Xylocarpus mekongensis* Pierre.**	Passur	*Meliaceae*	O, M, P	WH, WO	S

*** Indicates mangrove associates according to Tomlinson (2016). Abbreviation: Salinity zone- O = oligohaline, M = Mesohaline, P = Polyhaline. Inundation: WL = Waterlogged during Low tide, WH= Waterlogged during High tide, WO = Waterlogged Occasionally. Successional stage: Pr = Pioneer, S = seral and C = Climax. Source: Siddiqi (2001); Mahmood (2015); Rahman et al. (2015); Islam (2016); Sarker et al. (2016)**

Table A.2 Two-way ANOVA results for SOCD (gm cm^{-3}) in different salinity zones and soil depths.

Source	DF	SS	MSS	F	p
Soil Depth	3	6.4	2.1	30.1	<0.0001
Salinity Zone	2	15.9	7.9	112.3	<0.0001
Soil Depth*Salinity Zone	6	1.5	0.2	3.5	<0.01
Residuals	500	35.5	0.07		

Table A.3 Two-way ANOVA results for Bulk density (gm cm^{-3}) in different salinity zones and soil depths.

Source	DF	SS	MSS	F	p
Soil Depth	3	0.9	0.3	46.2	<0.0001
Salinity Zone	2	0.3	0.2	22.2	<0.0001
Soil Depth*Salinity Zone	6	0.01	0.003	0.5	>0.5
Residuals	500	3.5	0.007		

Table A.4 Two-way ANOVA results for SOC (Mg ha^{-1}) storage in different salinity zones and soil depths.

Source	DF	SS	MSS	F	p
Soil Depth	3	108.7	36.2	526.2	<0.0001
Salinity Zone	2	16.4	8.2	118.9	<0.0001
Soil Depth*Salinity Zone	6	1.4	0.2	3.3	<0.003
Residuals	500	34.4	0.07		

Table A.5 One-way ANOVA result for SOC in different forest types.

Source	DF	SS	MSS	F	p
Forest types	7	5704	8149	3.3	<0.01
Residuals	47	11715	249.3		

Table A.6 Tukey HSD Post-hoc test for the average soil organic carbon (SOC) (Mg ha^{-1}) in different forest types. Different letters indicate significant differences at P<0.05. Data are mean ±Standard Deviation (SD).

Forest Types	**SOC (Mg ha^{-1})**		
	Mean	± SD	HSD rank
***Bruguiera* sp.**	105.3	3.6	a
Sonneratia sp.	68.7	20.1	ab
Avicennia sp.	67.1	9.3	ab
***Heritiera* sp.**	67.0	13.2	b
MIXED	61.3	28.7	b
***Xylocarpus* sp.**	58.8	4.6	b
***Excoecaria* sp.**	56.3	15.9	b
***Ceriops* sp.**	50.2	9.7	b

Table A.7 PCA (Principal Component Analysis) results based on soil physical, chemical properties and vegetation properties. Bold values correspond highly correlated values (PCs > 0.35) and underlined values represent non-correlated variables with the respective PCs highest loading.

Principal Component	**PC1**	**PC2**
Eigenvalue	4.95	1.97
Percentage of total variance (%)	49.5	19.8
Cumulative percentage (%)	49.5	69.3
BD	-0.27	0.02
pH	**-0.36**	0.24
SS	**<u>-0.37</u>**	0.29
TD	-0.33	-0.25
DBH	0.26	**<u>0.49</u>**
H	0.34	**0.38**
E	-0.32	-0.32
C/N	0.21	**<u>-0.40</u>**
LAT	0.33	-0.31
LONG	0.32	-0.17

Table A.8 Step-wise multiple linear regression

Model		**Unstandardized coefficient**		**Standardized coefficient**	**t**	**Significance**	**Lower**	**Upper**
		β	Standard error	Beta				
1	(Intercept)	4.449	0.057		78.161	0.000	4.335	4.563
	Soil Salinity	-0.111	0.015	-0.712	-7.391	0.000	-0.141	-0.081
2	(Intercept)	3.594	0.270		13.330	0.000	3.053	4.135
	Soil Salinity	-0.083	0.016	-0.534	-5.106	0.000	-0.116	-0.050
	Ln (C: N)	0.273	0.085	0.338	3.230	0.002	0.103	0.443
3	(Intercept)	3.439	0.263		13.072	0.000	2.911	3.967
	Soil Salinity	-0.077	0.016	-0.499	-4.972	0.000	-0.109	-0.046
	Ln (C: N)	0.274	0.080	0.339	3.415	0.001	0.113	0.436
	Mean DBH	0.017	0.007	0.220	2.579	0.013	0.004	0.031

Dependent variable: Ln (SOC)

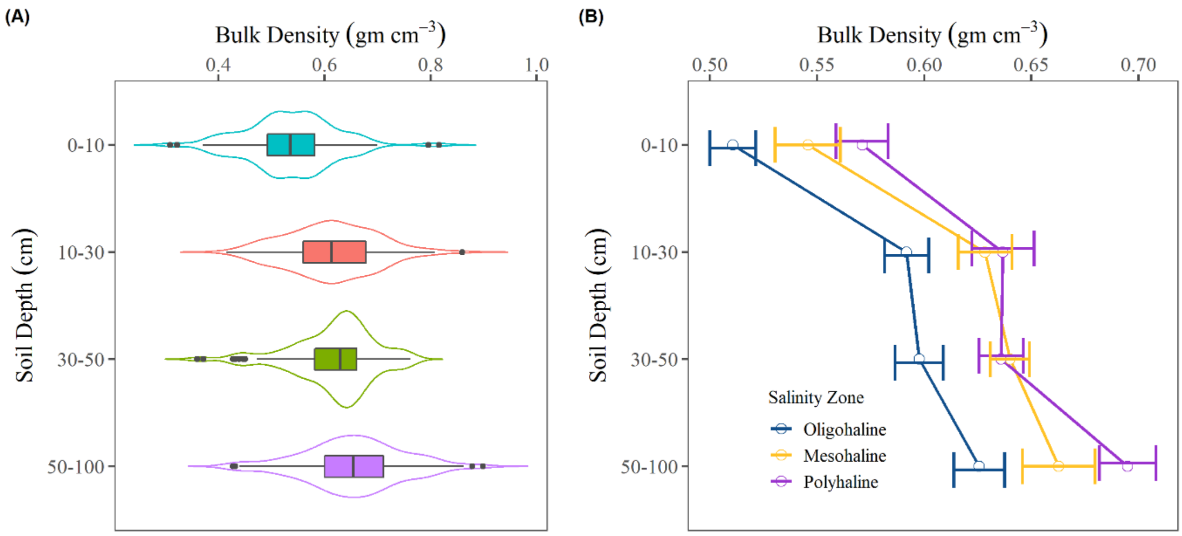

Fig. A.1. (A) Integrated violin-box plot shows the distribution of bulk density in four soil depth, where the black dots are outliers. (B) Average bulk density in three salinity zones and four soil depths.

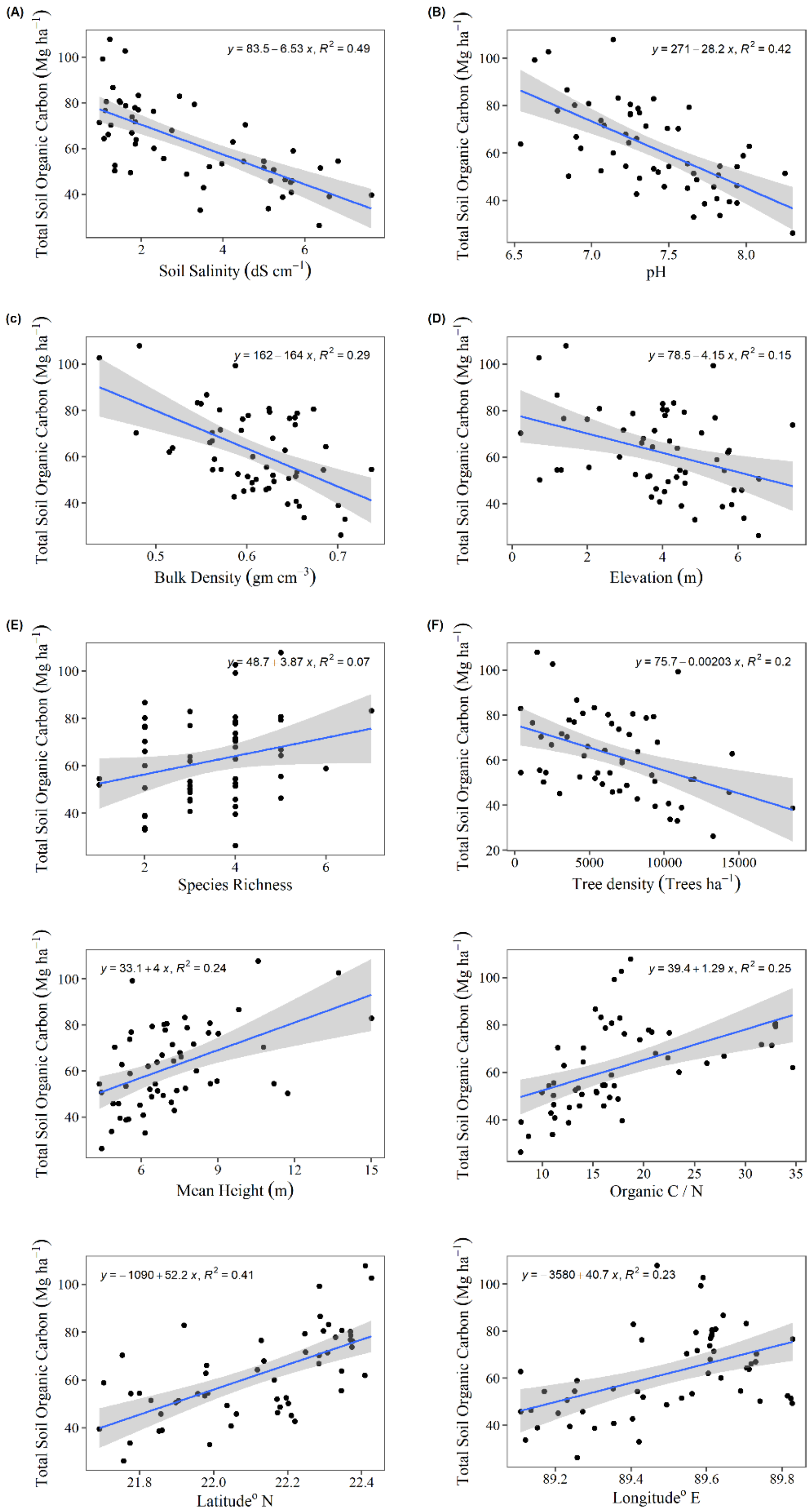

Fig. A.2. Bivariate relationship between soil organic carbon with different soil physicochemical, geophysical properties and vegetation characteristics in the Sundarbans.

Supplementary References

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