

Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones

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Abstract The Sundarbans (21°30′–22°30′ N and 89°00′–89°55′ E) is the largest mangrove forest in the world. Forests are very important for sequestering atmospheric carbon and mangroves are amongst the most efficient in carbon sequestration. This study presents the estimation of ecosystem carbon (above- and belowground) stock in the Sundarbans using a large scale data sets collected from systematic grid samples throughout the forest. The variation of carbon stock in different vegetation types and in different salinity zones in Sundarbans was investigated. The relationships between carbon stock and different vegetation functional attributes (basal area, mean tree height, crown coverage etc.) were also investigated. The amount of carbon stored varied significantly among vegetation types, salinity zones and vegetation functional attributes ($P < 0.05$). Sundri (*Heritiera fomes*) dominated forest types store more ecosystem carbon ($360.1 \pm 22.71 \text{ Mg C ha}^{-1}$) than other vegetation types. The fresh water zone shows the highest ecosystem carbon stock ($336.09 \pm 14.74 \text{ Mg C ha}^{-1}$) followed by moderate and strong salinity zones.

Salinity was found to enhance belowground carbon stock as revealed by the lowest proportion of belowground carbon stock (57.2 %) with respect to ecosystem carbon in fresh water zone and by the highest (71.9 %) in strong salinity zone. The results also reveal that no matter whether the mangroves are tall or dwarf, a significant amount of carbon is stored into the sediment. The vegetation attributes (basal area and mean tree height) of the dominant mangrove species in each vegetation type were identified as the key indicator of ecosystem carbon stock. We recommended some generalized regression equations to predict ecosystem carbon stock from basal area or mean tree height.

Keywords Carbon sequestration · Aboveground carbon · Belowground carbon · REDD+ · Vegetation functional attributes · Ecosystem carbon

Introduction

The World today is facing major challenges caused by atmospheric CO₂ causing global warming (IPCC 2013). Global warming is mostly due to man-made emissions of greenhouse gases (mainly CO₂) (IPCC 2013). Combustion of fossil fuel and deforestation are the two main sources of CO₂ emission to the atmosphere (Detwiler and Hall 1988; Woodwell et al. 1983). It has been predicted that atmospheric

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CO₂ will range between 467 and 555 ppm by the year 2050, which ranged between 278 ppm in 1750 and 390 ppm in 2011 and that the average global temperature will increase by 2–42 °C by the year 2050 (IPCC 2007; IPCC 2013; Anderson and Bows 2011). The global warming of this magnitude could significantly alter the earth's climate, land use, and major vegetation zones and perhaps more importantly melting of polar ice to raise sea level by 5 m causing severe loss of life and property (Detwiler and Hall 1988; IUFRO 2009), especially in the developing countries. Bangladesh is among the most vulnerable countries affected by global warming.

Forests play an important role in mitigating global climate change through sequestering atmospheric carbon (Adame et al. 2013). Mangroves are particularly efficient sinks, sequestering four times carbon per unit area compared with terrestrial forests in the tropics (Khan et al. 2007; Donato et al. 2011). However, deforestation of mangroves, which was very widespread in the last few decades (Giri et al. 2011), may render them significant sources of atmospheric carbon (Donato et al. 2011) and policy makers are looking at new ways to save this unique ecosystem through different mitigation approaches such as 'Reducing emissions from deforestation and forest degradation (REDD+)'. So, in order to participate in UNFCCC's mitigation programs (e.g., REDD+) and thereby generate economic benefit for the country, it is imperative to make a baseline assessment of the ecosystem carbon stock (Adame et al. 2013).

In mangrove forests carbon sequestration (e.g., Khan et al. 2007; Bouillon et al. 2008) and organic carbon dynamics (Machiwa and Hallberg 2002; Kristensen et al. 2008) have been studied much. Carbon stock in mangrove ecosystem varies with species (Laffoley and Grimsditch 2009), vegetation type (Adame et al. 2013; Cerón-Bretón et al. 2011; Mitra et al. 2011; Sapit et al. 2011; Laffoley and Grimsditch 2009) and salinity (Adame et al. 2013). However, less attention has been paid on the spatial variation of carbon stock among different vegetation types and variation in the above- and belowground carbon.

The Sundarbans is the largest single tract of mangrove forest in the world (6,017 sq km in Bangladesh and 4,000 sq km in India). It is a RAMSAR SITE having three wildlife sanctuaries which are designated as World Heritage by UNESCO during 1997. The forest is, nationally and

internationally, of great conservation significance for its environmental services and biodiversity (Seidens-ticker and Hai 1983; Iftexhar and Saenger 2008). To aid in conservation of the forest and to benefit from various global initiatives (e.g., carbon trading) an assessment of the carbon sequestration (above- and belowground) in Sundarbans is immensely important. Moreover, the heterogeneity of the mangrove forest in terms of large area of forest cover, salinity zone (Wahid et al. 2007), dominant mangrove types and vegetation functional attributes (basal area, mean tree height, canopy cover etc.), which might influence the aboveground and belowground carbon stock would be of great interest to mangrove ecologists. Therefore, the objectives of the present study were: (i) to estimate the carbon above- and belowground carbon stock in Sundarbans, (ii) to investigate the variation of carbon stock in different vegetation types and salinity zones in the forest and (iii) to establish a generalized method for assessing the ecosystem carbon stock in Sundarbans.

Materials and methods

Description of study area

The study was carried out in the Sundarbans, which lies between 21°30' N and 22°30' N and 89° 00' E and 89°55' E, in the southwest of Bangladesh. The forest covers an area of 6,017 km² (Bangladesh part) of which 4,120 km² are covered by the forests and the remaining 1,897 km² are in rivers, canals and creeks of varying width and depth (Islam 2011). The soil of the Sundarbans is silty clay loam with alternate layers of clay, silt and sand (Gopal and Chauhan 2006). Trees in the Sundarbans include 22 families representing 30 genera. Important tree species of the Sundarbans along with their life form are presented in the Table 1 (Iftexhar and Islam 2004). In Sundarbans there are ten prominent vegetation types (Table 2) (Chaffey et al. 1985; Iftexhar and Saenger 2008).

Sampling design

Through systematic grid sampling method, 155 plots (1,570.79 m² each) were selected at 4 min intervals of latitude and 2 min intervals of longitude. Of the 155 plots, five plots were fallen over water channels,

Table 1 Life form characteristics of main flora in the Sundarbans

| Local name | Scientific name | Life form |
|------------------|-------------------------------|---|
| Amoor | <i>Amoora cucullata</i> | A small tree |
| Baen | <i>Avicennia officinalis</i> | A large tree |
| Bola | <i>Hibiscus tiliaceus</i> | A small tree and semi climbing liana |
| Dhundul | <i>Xylocarpus granatum</i> | A small tree |
| Gewa | <i>Excoecaria agallocha</i> | A fair sized tree |
| Golpata | <i>Nypa fruticans</i> | A palm with soboliferous stem |
| Goran | <i>Ceriops decandra</i> | A shrub with coppice like growth |
| Hantal | <i>Phoenix paludosa</i> | A small gregarious palm |
| Hargoza | <i>Acanthus ilicifolius</i> | A small prickly leaved shrub |
| Hodo(Tiger fern) | <i>Acrostichum aureum</i> | A rigid tufted fern under growth |
| Kankra | <i>Bruguiera sexangula</i> | A medium sized tree |
| Keora | <i>Sonneratia apetala</i> | A large tree generally with spreading habit |
| Kewa kanta | <i>Pandanus odoratissimus</i> | A gregarious screwpin under-growth |
| Passur | <i>Xylocarpus mekongensis</i> | A fair sized tree |
| Sundri | <i>Heritiera fomes</i> | A fair sized tree |

Source (Siddiqi 2001)

Table 2 Major vegetation types in the Sundarbans with distribution and area

| Code | Vegetation type | Distribution in Saline zone | Area % |
|------|---|-----------------------------|--------|
| VT1 | Sundri | FR | 21.0 |
| VT2 | Sundri–Gewa | FR, MO and ST | 25.8 |
| VT3 | Sundri–Passur–Kankra | FR,ST | 1.7 |
| VT4 | Gewa Mathal, Passur–Kankra–Baen, Sundri–Passur–Keora, | FR, MO and ST | 2.9 |
| VT5 | Gewa | MO | 5.2 |
| VT6 | Gewa–Sundri | MO,ST | 18.4 |
| VT7 | Non tree vegetation (NTV) | FR,ST | 1.2 |
| VT8 | Goran–Gewa | MO, ST | 13.7 |
| VT9 | Goran | ST | 1.6 |
| VT10 | Gewa–Goran | MO, ST | 8.4 |

FR fresh water zone, MO moderate saline zone, and ST strong saline zone

Source (Chaffey et al. 1985; Iftexhar and Saenger 2008)

and the remaining 150 sample plots (total sample area of 23.56 ha) were considered for this study (Fig. 1). In each sample plot, five circular plots of 10 m radius were used for data collection (Fig. 3). These five subplots were nested and arranged in a cluster manner (Fig. 2) in Sundarbans carbon inventory. The cluster plot designs tend to capture more microsite variation in vegetation, soils, etc., thereby reducing among-plot variation (Pearson et al. 2005).

From the centre subplot, the other four subplots (Fig. 3) were arranged towards the four cardinal directions with a distance of 50 m (Ahmed and Iqbal 2011). The vegetation type and salinity zone for each plot were determined from the Sundarbans vegetation map and salinity map developed by Chaffey et al. (1985). The formation of salinity zones in Sundarbans is a recognized phenomenon (Wahid et al. 2007).

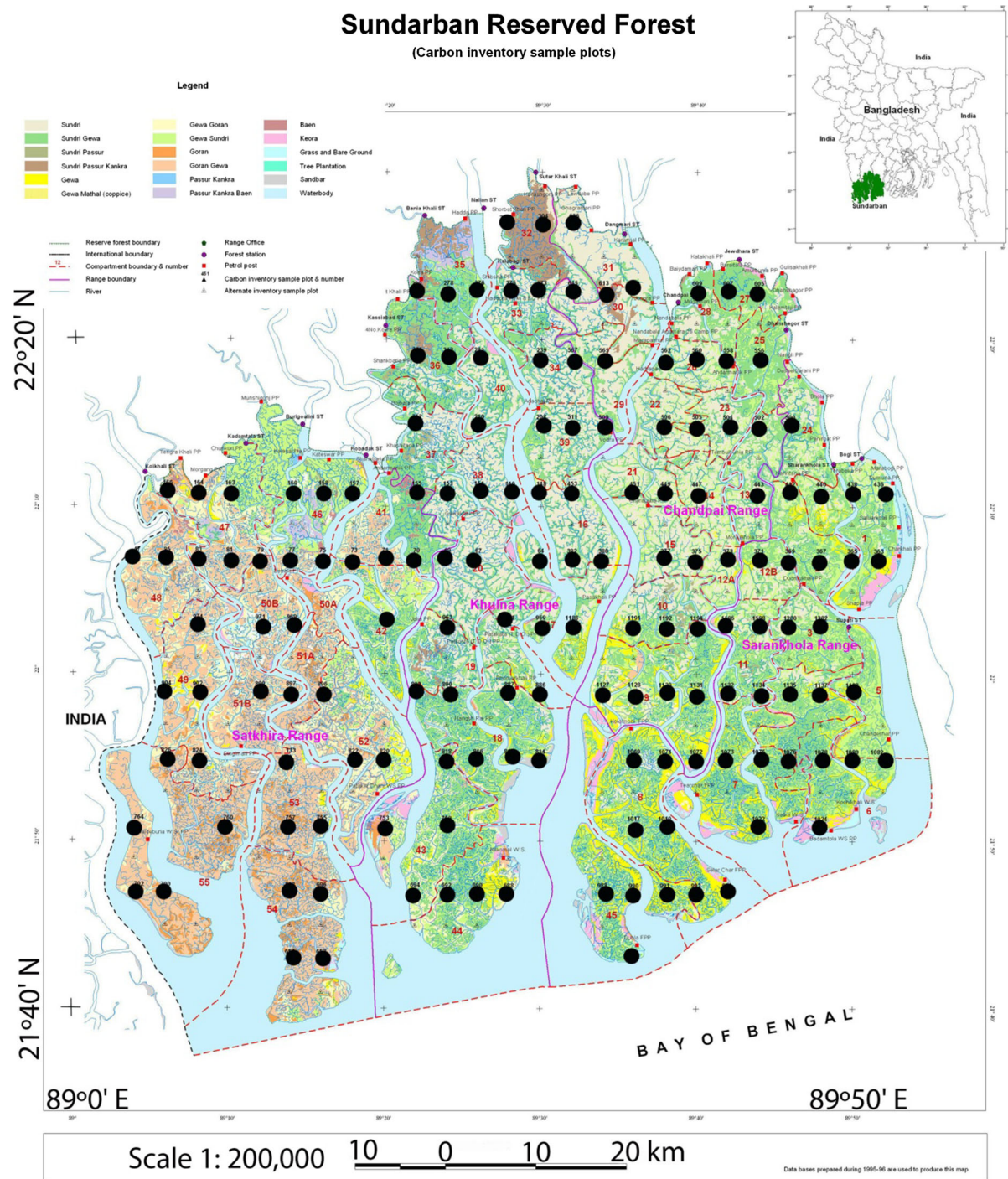


Fig. 1 Location of sample plots (black circles) in Sundarbans mangrove forest, Bangladesh

Tree inventory

Within 10 m radius from the centre of each subplot, diameter of all trees (live or dead with

diameter ≥ 10 cm at breast height (bh) was measured. The height of three co-dominant trees within each of the five subplots (Fig. 2) was measured with digital range finder. Species name, diameter at breast height

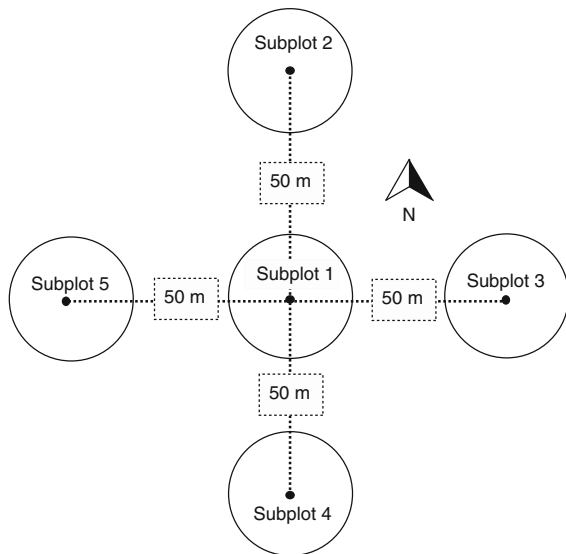


Fig. 2 Cluster plot composed of five nested subplots in a main plot

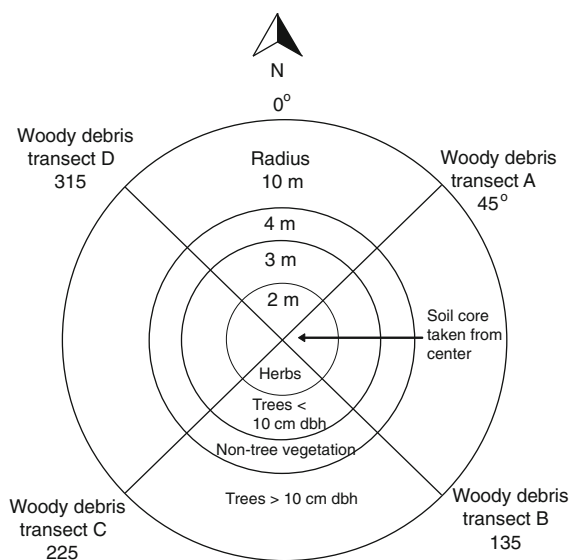


Fig. 3 Layout of a nested subplot

(dbh), living status and height in case of dead and broken trees was recorded. For saplings (diameter < 10 cm at bh) data were recorded as it was done for trees but within 3 m radius from the center of each of the five subplots in a sample plot (Fig. 3). However, for seedlings (trees < 1.3 m high), the number of individuals and the dominant species were recorded.

Table 3 Average biomass of species developed by destructive process

| Species name | Average biomass (kg) |
|------------------------|----------------------|
| Golpatta (per frond) | 2.00 |
| Tiger fern (Per clump) | 0.30 |
| Hargoza (Per stem) | 0.05 |
| Pandanus | 0.29 |
| Goran (Small) | 0.0048 |
| Goran (Medium) | 0.37 |
| Goran (Large) | 3.64 |
| Goran (Extra large) | 10.55 |

Palms with woody trunks, but not reaching breast height were counted as seedling.

Woody debris survey

Mass of dead tree (that lean at an angle > 45° from true vertical) and downed wood materials (twigs, branches or stems of trees or shrubs) that have fallen and lies up to a height of 2 m above the forest floor, was estimated by using planar intersect technique (Van Wagner 1968; Harmon and Sexton 1996). In each subplot (10 m radius), four 10 m long transects were laid out; of which first one was directed to 45° from the subplot centre and the other three transects were established at clock wise of 90° off from the previous transect. Woody debris was categorized into four size classes: small (0–0.6 cm), medium (0.6–2.5 cm) large (2.5–7.6 cm), and extra-large (≥7.6 cm) (Brown 1971). Again, the extra-large class was divided into two subclasses: sound (machete bounces off or only sinks slightly when struck) and rotten (machete sinks deeply and wood is crumbly as it decomposed).

An aluminum downed-wood gauge (Fuel Gauge) was used to determine the size class of each piece encountered. Small, medium, and large pieces were tallied as the number of pieces that crossed the transect tape. For extra-large pieces the actual diameter over which the transect line was crossed was measured. Small pieces were only tallied for 2 m of transect (from meter 10 to meter 8), while medium pieces were only tallied for 5 m of transect (from meter 10 to meter 5) and the large and extra-large pieces were measured along the 10 m transect.

In order to quantifying specific gravity and quadratic mean piece diameter (small, medium and large),

21, 22, 20, 19, and 20 pieces of debris were collected respectively for small, medium, large, extra-large rotten, and extra-large sound size classes. The quadratic mean diameter of small, medium and large sized classes of woody debris was used to calculate the volume of these three classes (Brown 1971; Kauffman and Cole 2010).

Non-tree vegetation

Among the non-tree vegetation, goran (*Cerriops decandra*) and harbacious plants were measured within 2 m radius from the center of each of the five subplots, while other non-woody palms (e.g., *Nypa*), *Pandanus*, Tiger fern and woody shrubs were measured within 4 m radius (Table 1). Groan was tallied by 4 size classes (0–0.6 cm, 0.6–2.5 cm, 2.5–7.6 cm, >7.6 cm). For lianas dbh measurement was taken like as tree. Herbaceous vegetation was visually estimated and recorded as percent ground cover of herbs and grasses separately (USDA 2008). In case of *Nypa*, the number of stems rooted in the subplot was counted (not individuals or clumps, but separate stems), whereas for *Pandanus* and Tiger fern the number of clumps in the subplot was recorded.

Canopy cover

Canopy cover % was estimated by a spherical crown densitometer standing at the subplot center. To take readings, it was assumed that there are four equispaced dots in each square of the grid and systematically count the dots equivalent to quarter-square openings. Next the total count was multiplied by 1.04 to obtain percent of overhead area not occupied by canopy. The difference between this and 100 is an estimation of over story density in percent.

Soil sampling

Two soil samples (5 cm length) were collected at the midpoint of 0–30 and 30–100 cm depth intervals from each of the five subplots for determining soil bulk density and organic carbon concentration. Soil core of 1 m length was pulled out near the subplot centre by using a one meter long open face peat auger. Soil samples were air-dried in the field, oven-dried to constant mass at 60 °C (to stop microbial decomposition) at the Khulna IPAC cluster office for

determining bulk density, and then sent to Bangladesh Forest Research Institute (BFRI), Chittagong for carbon analysis. Soil carbon analyses were conducted in the laboratory of the soil sciences division of the BFRI. Soil sample were oven dried at 105 °C before homogenizing and organic carbon concentration was determined by following Walkley–Black’s wet oxidizing method (Nelson and Sommers 1996).

Biomass and carbon computation

Aboveground biomass of live trees, poles, saplings and dead ones (decay status 1: having stem, branch and twigs) was estimated by the following general equation (Eq. 1) for mangrove tree species (Chave et al. 2005)

$$AGB = \rho \cdot e^{\{-1.349+1.98 \cdot \ln(D)+0.207 \cdot \ln(D^2)-0.0281 \cdot \ln(D^3)\}} \quad (1)$$

where AGB = aboveground biomass, ρ = wood density, D = dbh. The wood density data were obtained from destructive samples supplemented with local literatures, World Agroforestry Database (Carsan et al. 2012) and the Global Wood Density Database (Chave et al. 2009; Zanne et al. 2009).

Belowground biomass of trees was computed by using the general mangrove equation (Eq. 2) of Komiyama et al. (2005), while for palms, it was conservatively took 15 % of aboveground biomass (because general mangrove equation for belowground biomass does not apply to palms) (Macdicken 1997).

$$BGB = 0.199 \cdot \rho^{0.899} D^{2.22} \quad (2)$$

where BGB = belowground biomass, ρ = wood density, D = dbh.

Pearson et al. (2005) equation was applied for computing the biomass of woody palms that reaching breast height. For dead trees having decay status-2 (trees with no twigs/small branches but had large branches or stem only) whose base diameter was smaller than DBH (due to decay at base), the standard calculation would result in artificially large top diameter. Therefore, it was adjusted base diameter for these records (relatively few) based on average ratio of dbh: base-diameter, which was 0.82. It also followed for heavily buttressed trees, for which standard calculations yielded artificially low or even negative top diameters; it was defined heavily

buttressed trees as those with a dbh: base-diameter ratio that was two standard deviations below the mean ratio. For small palms not reaching dbh, these were measured as non-tree understory and a destructive harvest was carried out to estimate average biomass per understory palm. The short stumps, those not reaching breast height, were simply modeled as a cylinder shape to obtain volume, and then multiplied by species-specific wood density. For belowground biomass of these individuals, the base diameter was used to estimate the projected dbh based on the average ratio of dbh to base diameter (0.82), and then entered this into the equation.

In case of some non-tree vegetation including seedling, subsamples were collected from each destructively harvested individual to determine moisture content. The wet: dry ratios were averaged over the whole sample, then this average value applied to each individual (Table 3). Lianas biomass was quantified by using Schnitzer et al.'s (2006) allometric equation.

To calculate the mass of downed wood, it is necessary to know the mean specific gravity of the downed wood in the mangroves as well as quadratic mean diameters for the wood size classes <7.6 cm diameter (debris diameter greater than 7.6 cm were measured in the field) (Kauffman and Cole 2010). The quadratic mean diameter for small, medium and large was 0.45, 1.21 and 3.17, respectively. The mean specific gravity was 0.59, 0.55, 0.49, 0.25 and 0.40 g cm⁻³, respectively for small, medium, large, extra-large rotten and extra-large sound. By using these specific gravity and mean quadratic data, woody debris biomass was estimated via standard volumetric equations (Brown 1971).

Conversion of dry biomass of trees, understory, and downed wood to carbon mass was done by multiplying 0.5 as forest biomass contains half carbon by mass (Gifford 2000). Soil C stock was determined as the product of soil carbon concentration, bulk density, and depth intervals (Donato et al. 2011). The total carbon stock per plot was calculated by adding each of the carbon pool of the five subplots as below:

$$\begin{aligned} \text{Total C stock} = & C_{\text{treeAG}} + C_{\text{treeBG}} + C_{\text{deadtree}} \\ & + C_{\text{sapling}}_{\text{seedlingAG}} + C_{\text{sapling}}_{\text{seedlingBG}} + C_{\text{deadsapling}}_{\text{seedling}} \\ & + C_{\text{nontreevegetation}} + C_{\text{woodydebris}} \\ & + C_{\text{soil}} \end{aligned} \quad (3)$$

Statistical analysis

At first a one sample Kolmogorov–Smirnov test (K–S test) was performed to check whether the carbon stock data under the subgroups of vegetation types and salinity zones are normally distributed. A one-way ANOVA was used to test the significance of the differences among the carbon stock in different partitions, vegetation types and salinity zones. In addition, a two-way-ANOVA was performed to investigate the interaction effect with vegetation types nested within salinity zones. For multiple comparisons among the variables Duncan Multiple Range Test (DMRT) was used. Finally, correlation analysis was performed to obtain some generalized regression equations in order to predict above- and belowground carbon stock from vegetation attributes, such as stand basal area or mean tree height. All the statistical and graphical analyses were performed using SPSS version 16 and R version 3.1.0 (R Core Team 2014).

Result

Vegetation types and carbon stock

Aboveground carbon

The carbon stock data under the subgroups of vegetation types and salinity zones showed normal distribution as tested with Kolmogorov–Smirnov test (K–S test). Among the vegetation types, VT1 showed significantly higher ($P < 0.05$) tree aboveground carbon (TAGC) stock (152.57 Mg ha⁻¹) than other vegetation types, whereas VT7 showed significantly higher ($P < 0.05$) shrubs and herbs carbon (SHC) stock (61.35 Mg ha⁻¹) than other vegetation types (Fig. 4). There was no significant difference ($P > 0.05$) in down wood carbon (DWC) among the vegetation types (Fig. 4). If the total aboveground carbon stock were considered, the VT1 again showed significantly higher ($P < 0.05$) carbon stock than other vegetation types. The lowest carbon stock of 45.24 Mg ha⁻¹ was found in VT8 (Fig. 4). The aboveground carbon stock showed no significant interaction effect ($P > 0.05$) between the vegetation types nested within salinity zones as tested with two-way-ANOVA.

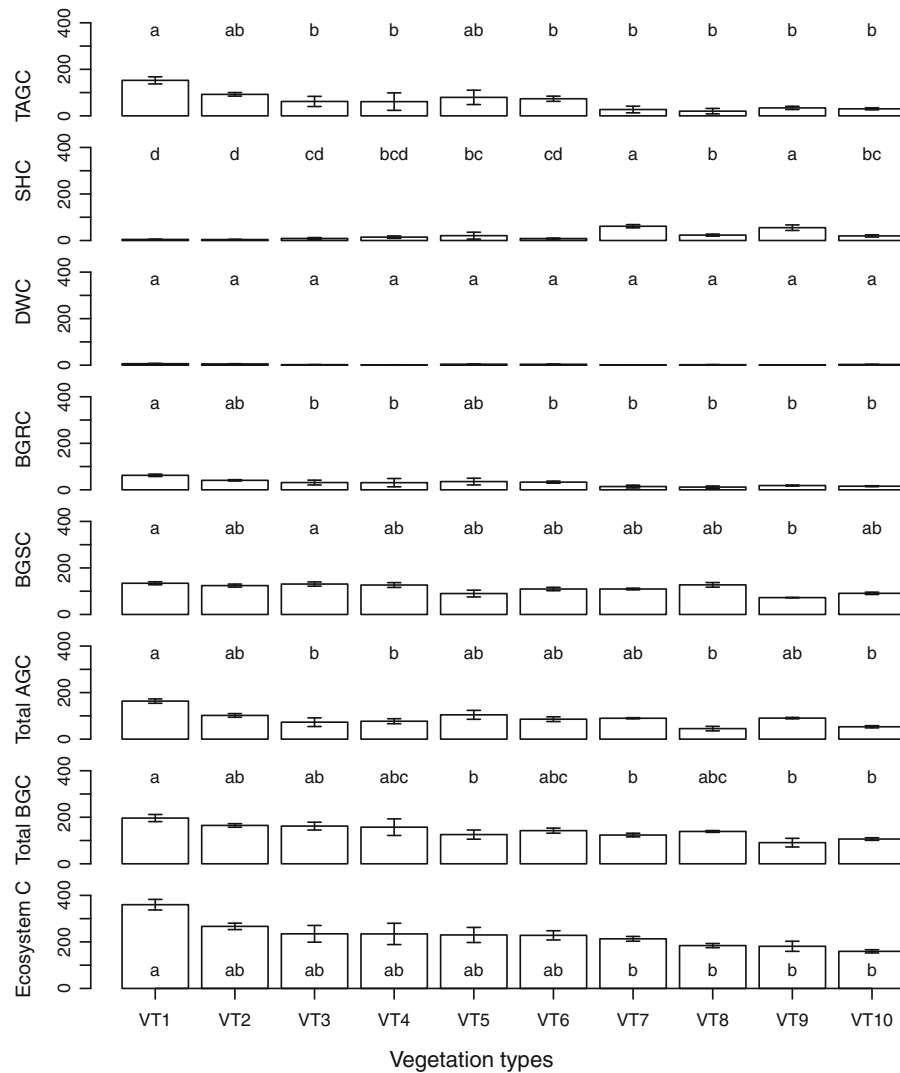


Fig. 4 Carbon stock (Mg ha^{-1} , Megagram per hectare \pm SE) in different partitions (TAGC tree aboveground carbon, AGC aboveground carbon, SHC shrubs and herbs carbon, DWC downed wood carbon, BGRC belowground root carbon, BGSC belowground soil carbon), in vegetation types (VT1 = Sundri, VT2 = Sundri-Gewa, VT3 = Sundri–Passure-Kankra,

VT4 = others (Gewa Mathal, Passur-Kankra-Baen, Sundri-Passur-Keora), VT5 = Gewa, VT6 = Gewa-Sundri, VT7 = Non tree vegetation, VT8 = Goran-Gewa, VT9 = Goran, VT10 = Gewa-Goran). The same letter(s) indicated on bars are not significantly different ($P > 0.05$) as tested with Dancun Multiple Range Test

Belowground carbon

As observed in the aboveground carbon, the belowground root carbon (BGRC) stock also showed significant differences among the vegetation types and the VT1 showed significantly higher ($P < 0.05$) carbon stock (62.37 Mg ha^{-1}) than other vegetation types (Fig. 4). The minimum amount (11.72 Mg ha^{-1}) of BGRC was observed in VT8. Although the

belowground soil carbon (BGSC) stock showed significant differences ($P < 0.05$) among the vegetation types, the BGSC stock showed a comparatively high range ($90.03\text{--}134.17 \text{ Mg ha}^{-1}$). If the belowground carbon stock were considered, the vegetation type VT1 showed significantly higher ($P < 0.05$) carbon stock ($196.54 \text{ Mg ha}^{-1}$) than other vegetation types and the minimum value (90.83 Mg ha^{-1}) was observed in VT9 (Fig. 4). The belowground carbon stock showed no

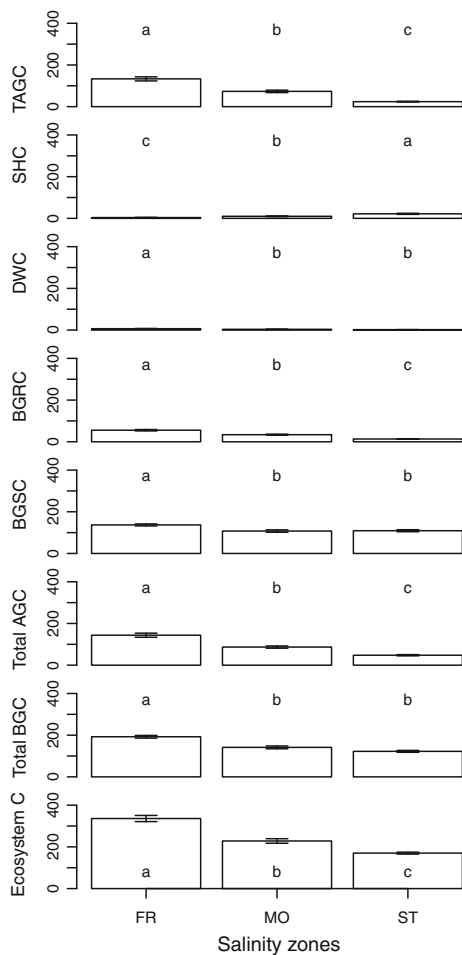


Fig. 5 Carbon stock ($\text{Mg ha}^{-1} \pm \text{SE}$) in different partitions (codes are same as Fig. 2) in salinity zones (FR fresh water zone, MO moderate saline zone and ST strong saline zone). The same letter(s) indicated on bars are not significantly different ($P > 0.05$) as tested with Duncan Multiple Range Test

significant interaction effect ($P > 0.05$) between the vegetation types nested within salinity zones as tested with two-way-ANOVA.

Salinity zone and carbon stock

The fresh water zone (FR) showed significantly higher ($P < 0.05$) carbon stock among the three major salinity zones (Fig. 5). The ecosystem carbon stock increased from strong salinity zone (ST) to moderate salinity zone (MO) to FR ($P < 0.05$; Fig. 5). This trend was observed in all the partitions (tree species, aboveground, BGRC, BGSC, downed wood, ecosystem) except in SHC stock ($P < 0.05$; Fig. 5).

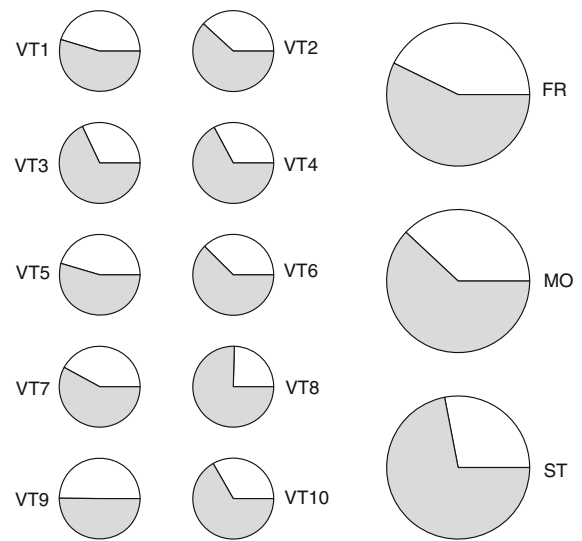


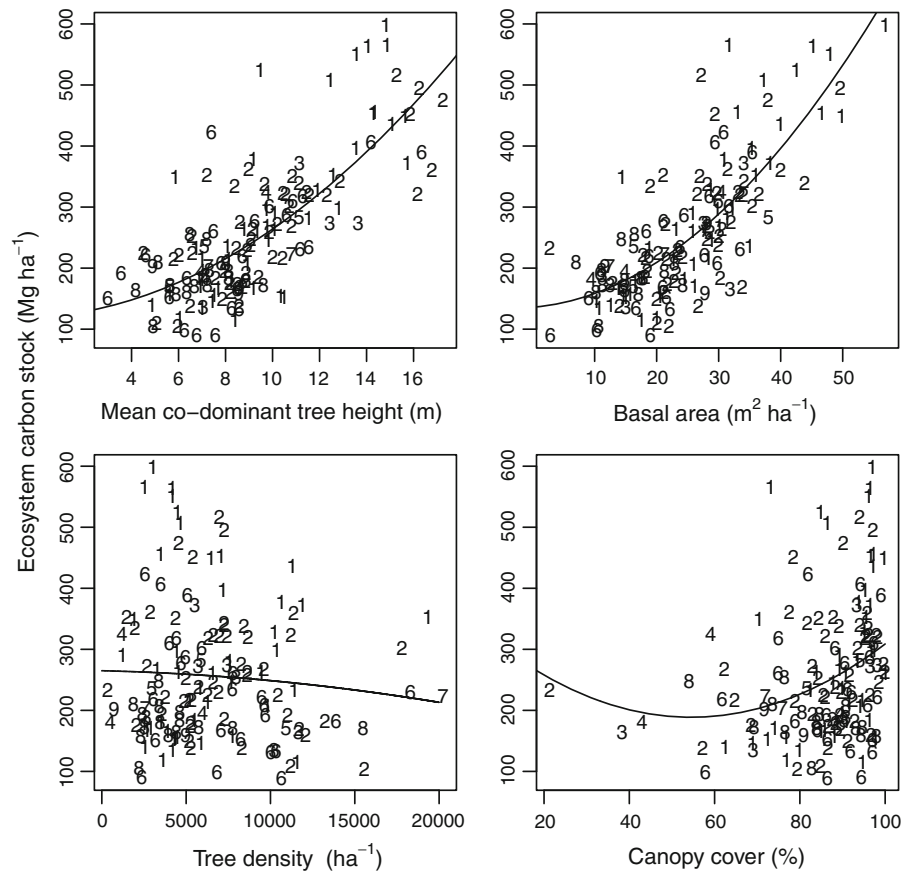
Fig. 6 Proportions of above- (white colored) and belowground (grey colored; including soil) carbon stock in relation to vegetation types (codes are same as Fig. 4) and salinity zones (codes are same as Fig. 5)

Ecosystem carbon stock

The ecosystem carbon stock ranged from $159.49 \pm 6.86 \text{ Mg ha}^{-1}$ in Gewa-Goran dominated vegetation type (VT10) to $360.01 \pm 22.71 \text{ Mg ha}^{-1}$ Sundri dominated VT1 (Fig. 4). VT1 showed significantly higher carbon stock than any other vegetation types (one-way-ANOVA, $P < 0.05$). As tested with DMRT, there was no significant difference in ecosystem carbon stock among the vegetation types VT2, VT3, VT4, VT5 and VT6 ($P > 0.05$; Fig. 4), followed by the next homogenous subset of comprising the vegetation types VT7, VT8, VT9 and VT10 ($P > 0.05$; Fig. 4).

If vegetation type is taken into account, it was found that the minimum proportion of belowground carbon stock constitute 50.15 % of the ecosystem carbon stock in VT9, which reaches up to 75.44 % in VT8 (Fig. 6). If ST is taken into account, the salt showed a positive influence with belowground carbon partitioning and it was found that the minimum proportion of belowground carbon stock constitute 57.24 % of the ecosystem carbon stock in FR, which reaches up to 71.95 % in strong salinity zone (ST) (Fig. 6). The ecosystem carbon stock showed no significant interaction effect ($P > 0.05$) between the vegetation types nested within STs as tested with two-way-ANOVA.

Fig. 7 Relationships of ecosystem carbon stock (Mg ha^{-1}) to mean co-dominant tree height (m) ($R^2 = 0.58$, $P < 0.05$), basal area ($\text{m}^2 \text{ha}^{-1}$) ($R^2 = 0.61$, $P < 0.05$), tree density (ha^{-1}) ($R^2 = 0.01$, $P > 0.05$) and canopy cover (%) ($R^2 = 0.09$, $P > 0.05$). Data points represents vegetation types (VT1 = 1, VT2 = 2, VT3 = 3, VT4 = 4, VT5 = 5, VT6 = 6, VT7 = 7, VT8 = 8, VT9 = 9, VT10 = 10; codes are same as Fig. 4). The curves were fitted using quadratic equation (Eqs. 4, 5)



Vegetation functional attributes and carbon stock

The ecosystem carbon stock were plotted against several vegetation functional attributes such as basal area (BA), mean co-dominant tree height (CDTH), tree density and canopy cover percent (CCP) considering all the vegetation types (Fig. 7) and all the STs (Fig. 8). It was found that BA holds a strong positive relationship ($R^2 = 0.61$, $P < 0.05$), which can be expressed by the following equation:

$$\text{EcosystemC} = 255.2 + 1016.6 \times \text{BA} + 239.3 \times \text{BA}^2 \quad (4)$$

The CDTH also showed a strong positive relationship ($R^2 = 0.58$, $P < 0.05$), which can be expressed by the following equation:

$$\text{EcosystemC} = 255.2 + 1007.4 \times \text{CDTH} + 171.2 \times \text{CDTH}^2 \quad (5)$$

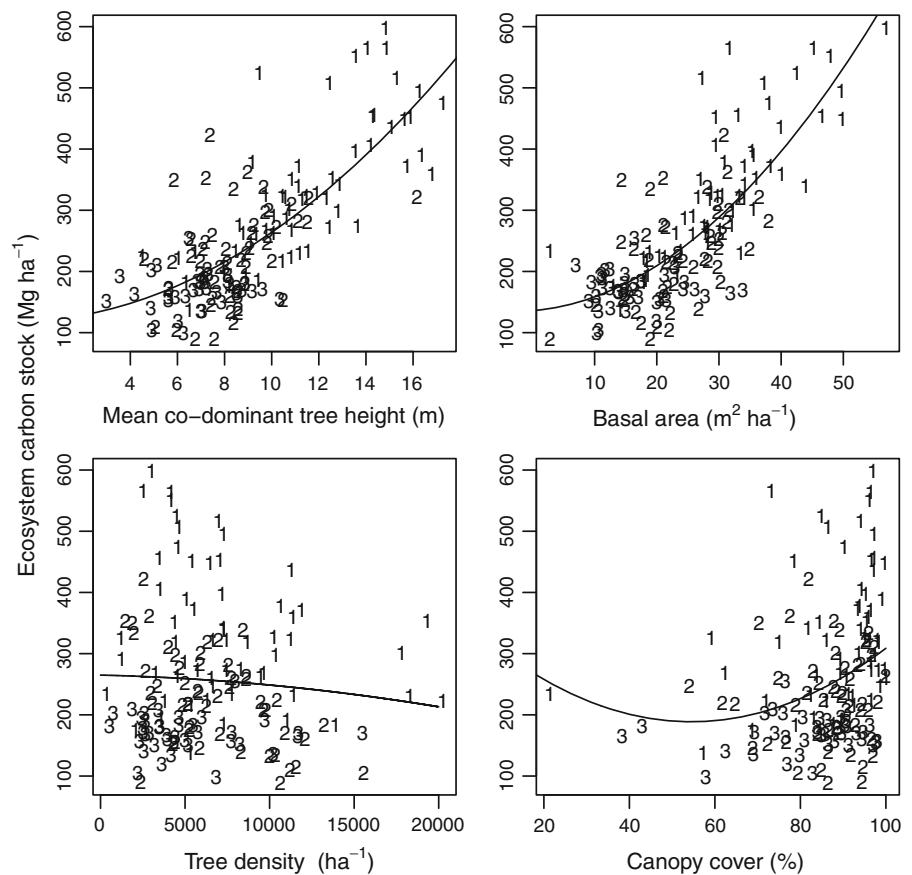
However, tree density and CCP showed weak relationships with ecosystem carbon stock.

Discussion

The richness of mangrove tree species in Sundarbans restricts the use of species-wise allometric equations for biomass estimation. Therefore, in this study we used universal allometric equations (Chave et al. 2005; Komiyama et al. 2005) for estimating the above- and below-ground biomass of tree species using the variables tree dbh and wood density, in order to avoid destructive sampling of trees.

The results of this study suggest significant differences ($P < 0.05$) in carbon stock among different mangrove vegetation types. However, no significant interaction effect ($P > 0.05$) of the vegetation types and nested within salinity zones on carbon stock was detected, which indicates that the variations of carbon

Fig. 8 Ecosystem carbon stock in relation to salinity zone. Data points represents salinity zone (1 = Fresh water zone, 2 = Moderate Saline zone and 3 = Strong Saline Zone). The curves were fitted using quadratic equation (Eqs. 4, 5)



stock are caused independently by vegetation types or salinity. Among the vegetation types, Sundri dominated forest contained highest amount of ecosystem (above- and belowground) carbon (360.0 Mg ha^{-1}) per unit area followed by Sundri-Gewa, Sundri-Passure-Kankra, others (Gewa Coppice, Passur-Kankra-Baen, Sundri-Passur), Gewa, Gewa-Sundri, non-tree vegetation, Goran-Gewa, Goran, and Gewa-Goran (Fig. 4). The reason behind this variation could be aboveground vegetation stature as the carbon stock was found strongly correlated with the size of the trees (height and diameter) and basal area. Klimešová et al. (2008), Westoby et al. (2002), Westoby (1998) also observed that trees attaining greater height outcompeting their neighbors accumulate more carbon. In a natural ecosystem, the diameter of the tree is a determinant of aboveground biomass (Chave et al. 2004). The dominant species in each vegetation type may have an effect on aboveground biomass depending on their basal area (Ruiz-Jaen and Potvin 2010) as observed in this study (Figs. 7 and 8). While canopy

cover is a weak indicator of carbon stock as in natural forest the canopy cover is formed by almost all the size classes of trees. Similarly, tree density forms a weak indicator of ecosystem carbon stock (Figs. 7 and 8), which is a general phenomenon, because a young forest with high density may show a lower biomass than in a low density mature forest. However, tree density may form a strong indicator of ecosystem carbon stock for cases such as Gross et al. (2014), when seedlings and saplings are few or absent. So, vegetation types with higher canopy height, trees having larger diameter and thus more basal area, contain more ecosystem carbon. It is important to note that Sundri is among the tallest tree species in the Sundarbans (height 15–21 m; Karim 1988) and comparatively large diameter (except Baen and Keora). Therefore, vegetation types with fewer or no Sundri have lower carbon stock.

Significant differences in ecosystem carbon stock were also observed in different STs in the Sundarbans. The FR contained the highest amount of carbon followed by moderately and strongly saline zones

(Fig. 5). In the Sundarbans as salinity increases plants become dwarfed. Here, salinity is highly dependent on the fluctuating volume of freshwater coming from the upstream (Wahid et al. 2007) and literally the absence of fresh water flow makes the strong saline zones. There is also spatial variation of nutrients in tidal water (Wahid et al. 2007). Therefore, the variation of carbon stock in different STs in Sundarbans could be due to adverse impact of increased salinity on the biomass productivity and due to spatial variation of fresh water nutrients (Wahid et al. 2007). Generally, in mangrove ecosystem especially in riverine mangrove forest, which experience of the incursion of larger amount of freshwater with fluvial nutrients (Kathiresan and Bingham 2001), there is a prominent tradeoff between salinity and the distribution of species, their productivity and growth of mangrove forests (Twilley and Chen 1998) and thus on carbon stock (Crooks et al. 2011). In mangrove ecosystem, vegetation is more abundant in lower STs where their productivity is higher and higher productivity means higher biomass and higher carbon stock (Crooks et al. 2011; Kathiresan and Bingham 2001; Ball 1998, 2002).

In this study it was found that, the contribution of Soil carbon (up to 1 m) to total ecosystem carbon stock was almost similar to total aboveground carbon stock both among the vegetation types and STs which reveals that mangroves can store larger amount of organic carbon into sediment (Bouillon et al. 2003; Khan et al. 2007; Donato et al. 2011). When soil carbon and root carbon are considered together, like other mangrove forests the contribution of belowground carbon to ecosystem carbon stock, was more than that of aboveground carbon (Kauffman et al.

2011; Donato et al., 2011; Adame et al. 2013). This is due to high root-shoot ratios in mangrove forest (Fujimoto 2004; Fujimoto et al. 1999; Page et al. 2002; Komiyama et al. 2000, 2008; Khan et al. 2007), which means that mangroves store a larger amount of carbon in soil at several meters depth (Bouillon et al. 2003).

The estimated carbon stock of vegetation types and STs, were similar to Indian Sundarbans and mangrove ecosystems in Northwestern Madagascar (Table 4). However, comparing with Indo Pacific region and Mexican Caribbean mangroves (soil carbon up to 1 m), our results are much lower, such as the *Sonneratia alba* dominated Mangrove in Yab, Micronesia, the *Rhizophora apiculata* dominated Mangrove in Babeldoab, Republic of Palau), the *Rhizophora apiculata* and *Bruguiera gymnorhiza* dominated Mangrove in Kalimantan, Indonesia and the *R. mangle* mangroves of the Sian Ka'an Biosphere Reserve, Mexico (Table 4). This differences in mangrove carbon stock would occur due to the amount of peat soil (Smith 1983a, b; crooks et al. 2011; Siikamäki et al. 2012), mineral sediment (Crooks et al. 2011; Siikamäki et al. 2012), stature of aboveground vegetation (Murdiyarso et al. 2010), wood density (Baker et al. 2004), forest age (Kridiborworn et al. 2012; Cerón-Bretón et al. 2011), disturbance history (Goode et al. 2002), dominant species (Ksawani et al. 2007), the depth of the organic soil, salinity, available soil phosphorus (Adame et al. 2013).

In conclusion, this study presents estimates of ecosystem carbon stock of a large mangrove forest, the Sundarbans using data sets covering widely distributed samples. The results suggest the existence of significant variations of carbon stock in different

Table 4 Comparison of ecosystem carbon stock (Above- and belowground; soil carbon up to 1 m depth) of current study to other mangroves of the world

| Source | Site | Ecosystem carbon stocks (Mg C ha ⁻¹) |
|------------------------|--|--|
| Present study | Vegetation types, Sundarbans | 159.5–360.0 |
| Present study | Salinity zones, Sundarbans | 170.1–336.1 |
| Donato et al. 2011 | Indian Sundarbans | ~212.5–312.5 |
| Kauffman et al. 2011 | Mangrove in Yab, Micronesia | 897.8 |
| Kauffman et al. 2011 | Mangrove in Babeldoab, Republic of Palau | 618.3 |
| Murdiyarso et al. 2010 | Mangrove in Kalimantan, Indonesia | 488 |
| Adame et al. 2013 | Sian Ka'an biosphere reserve, Mexico | 631.33 |
| Jones et al. 2014 | Mangrove ecosystems in northwestern Madagascar | 443.2 |

mangrove vegetation types and different zones of the forest having variable salinity regimes. The vegetation attributes (basal area and height) of the dominant mangrove species in each vegetation type are the key indicator of determining the nature of ecosystem carbon stock. The results also reveal that no matter whether the mangroves are tall or dwarf, a significant amount of carbon is stored into the sediment, which is a characteristic feature of mangroves. For a gross estimation of ecosystem carbon stock, the generalized regression equations (Eqs. 4, 5) with variables, such as ‘basal area’ or ‘mean tree height’ could be very useful not only for Sundarbans mangrove but also for other mangroves as the results were obtained from a wide variety of mangrove vegetation types and from large scale spatial distribution of samples. The results of this study might be of use for the policy makers to develop suitable adaptive measures to cope with the trends of sea level rise, that is projected to upturn (IPCC 2013). Future studies should focus to find out the driving forces other than salinity of the so called ‘salinity zones’ in the Sundarbans, which might influence the differences in vegetation patterns as well as carbon sequestration in these zones.

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