Stand structure and carbon storage in the oligohaline zone of the Sundarbans mangrove forest, Bangladesh

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ABSTRACT
A mangrove community along the oligohaline zone of the Sundarbans Reserve Forest (SRF), Bangladesh was selected to study stand structure, biomass accumulation, and carbon storage. Field data were measured from six plots of 2400 m$^2$ at three different locations. Species diversity and species wise contribution to total biomass carbon (TBC) were also analyzed. *Heritiera fomes* has maintained its dominance (53.8%, relative density) of the stand. The mean above- and below-ground biomass carbon stock of the mangrove community was 76.8 Mg ha$^{-1}$ and 41.1 Mg ha$^{-1}$, respectively. *Avicennia officinalis* contributed the highest TBC accumulation. Individuals of different mangrove species having diameter $\geq$ 9.99 cm constituted more than 72% of the mangrove stand but contributed less in carbon accumulation, representing only 15.6% of the TBC. While individuals having diameter in the 10–56 cm range constituted only 28% of stand density but contributed to high carbon accumulation, representing 84.4% of the TBC. Mangrove communities growing along the oligohaline zone of the SRF show high species richness and carbon stock, indicating their ecological significance. This needs to be considered in future decision making processes for the area as well as in understanding the role of SRF on mitigating the effects of climate change.

Introduction
As well as being unique wetland ecosystems in intertidal coastal regions of the tropics and subtropics, mangrove forests are among the world's most productive ecosystems (Lugo and Snedaker 1975; Nagarajan et al. 2008). Biomass and productivity have been studied in different mangrove forests around the world (e.g., Putz and Chan 1986; Day et al. 1996; Sainthil 1997; Komiyama et al. 2000), mainly in order to help inform ecosystem management and evaluate carbon stocks in mangrove communities (Kauffman et al. 2011; Wang et al. 2013; Liu et al. 2014; Sitoe et al. 2014). Patterns of carbon accumulation and its relationship to species dominance (richness) and individual tree size is determined by the age and size distribution of trees in stands and the history of stand development in the area.

The Sundarbans, the world's largest continuous patch of mangrove forest, is located in the estuary of the river Ganges-Brahmaputra. The forest is distributed over two neighboring countries, Bangladesh and India. In Bangladesh the forest covers 6017 km$^2$ (21°30'–22°30' N, 89°00'–89°55' E). Chaffey et al. (1985) divided the Sundarbans mangrove forest into three ecological zones: fresh water (oligohaline); moderately saline water (mesohaline); and salt water (polyhaline). Changes in salinity might be responsible for the spatial distribution of plant communities (Ahmed et al. 2011).

Very few previous studies have examined the stand structure, biomass, and carbon storage of Sundarbans Reserve Forest (SRF), Bangladesh with respect to its biodiversity and role as a carbon sink among the other forest ecosystems in the tropics (Iftekhar and Saenger 2008; Ahmed et al. 2011; Rahman et al. 2015), and no previous studies have examined the species wise contribution to the total carbon stocks of the mangrove communities in this area. In the present study, the structural characteristics of the mangroves within the oligohaline zone have been quantified with a view to assessing their role in total carbon stocks of the SRF, Bangladesh.

Stand structure of mangroves may directly influence the conditions and functioning of mangrove ecosystems, and its alteration may change the distribution and abundance of these ecosystems' fauna (Cavalcanti et al. 2009). Therefore, it is important to know the stand structure in order to understand the potential responses of mangrove ecosystems to environmental factors. Thus, the objectives of this study were to characterize the stand structure of mangrove forests along the oligohaline zone of SRF and assess their role in carbon storage. Species diversity, above- and below-ground biomass carbon, and its relationship to different parameters such as tree diameter class and species wise contribution were also examined and presented.

Materials and methods

Study site
The study was conducted in the Dhangmari, Karamjol, and Ghagarami areas of the SRF from 7 to 20 March 2016. These areas receive regular tidal inundation via the River Passur. The mean annual rainfall in the region, with 80% probability, varies from about 2000 mm in the east to 1600 mm in the west. The rainy season is June to September; October to February is considered winter. Higher temperatures (26–34 °C) occur during...
March to June and lower temperatures (12–25 °C) during December to February. The annual relative humidity varies from 70%–80% (Rahman and Asaduzzaman 2010). We established two plots (20 m × 20 m) in each site, located in the oligohaline zone of the Sundarbans. The six plots covered 2400 m² in our study area; all the plots were c. 200 m from the shore to avoid damage from river erosion and storms.

**Forest structure**

Six mangrove species grow at the study site: *Heritiera fomes* Buch-Ham. (Malvaceae); *Excoecaria agallocha* L. (Euphorbiaceae); *Bruguiera sexangula* (Lour.) Poir. (Rhizophoraceae); *Aglaya cucullata* (Roxb.) Pellegr. and *Xylocarpus mekongensis* J. Koenig (Meliaceae); and *Avicennia officinalis* L. (Avicenniaceae). Structural characteristics (diameter at breast height [DBH] and height) of the mangrove stands are the primary determinants of carbon storage. So all trees in the study plots larger than 1.8 cm DBH were numbered and height (H) and DBH were measured in March 2016. The mean density (± SE) of the study area was 2629 ± 530 ha⁻¹, the mean height (± SE) was 8.9 ± 1.4 m, and the mean DBH (± SE) was 8.7 ± 1.5 cm as of March 2016. Structural indices were calculated: complexity index (Iₙ): number of species × density × basal area × mean height × 10⁻⁵; and importance value (Iᵥ): relative density + relative frequency + relative dominance (Cintron and Schaeffer-Novelli 1984).

Species diversity of each plot was determined by Margalef index (R), Shannon-Weiner index (H), and Simpson index (S) established by Margalef (1978), Shannon and Weiner (1963), and Simpson (1949), respectively. Evenness characteristics of the mangrove community was determined by Pielou index (J) established by Pielou (1966).

**Biomass and carbon estimation**

Although allometric relationships have been developed between DBH and weight for a number of mangrove species around the world, biomass production depends on the interaction between edaphic, climatic, and topographic factors of the specified area and the species that occur in the specific area. Unfortunately there is no developed allometric equation for biomass estimation of the studied mangrove species encountered in this study. So we tentatively apply the following above-ground biomass equation for all the mangrove tree species (Chave et al. 2005).

\[
AGB = \rho \times \exp(-1.349 + 1.980\ln(D) + 0.207(\ln(D))^2 - 0.0281(\ln(D))^3)
\]

(1)

where \( AGB = \) above-ground biomass, \( \rho = \) wood density, \( D = \) DBH. The wood density data were obtained from Global Wood Density Database (Chave et al. 2009).

Below-ground biomass of mangrove tree species was estimated using a common allometric relationships between DBH and biomass established by Komiyama et al. (2005):

\[
BGB = (0.199 \cdot \rho^{0.999} D^{3.22})
\]

(2)

where \( BGB = \) below-ground biomass, \( \rho = \) wood density, \( D = \) DBH. The biomass calculation for individual trees of each species was estimated using the same allometric equation. The common allometric relationship for root weight was derived from the relationship between below-ground and above-ground weight of trees, so wood density is the same for both above-ground and below-ground weight estimation. Conversion of biomass of trees to carbon mass was done by multiplying forest biomass by 0.5 as carbon concentration is regularly 50% (Gifford 2000).

**Statistical analysis**

Data analysis was done by using Microsoft Excel 2007 software (Microsoft, Redmond, WA, USA). Figures were drawn using KaleidaGraph v 4.1 (Synergy software, USA).

**Results**

**Stand structure**

Structural composition of mangrove communities along the oligohaline zone of SRF and their structural composition are presented in Table 1. The preponderance of *H. fomes* gives it a high importance value index (Iᵥ = 106.1) in the study area. The Iᵥ for *E. agallocha*, *A. officinalis*, *X. mekongenisis*, *B. sexangula*, and *A. cucullata* were 59.3, 54.3, 39.6, 35.2, and 5.6, respectively. The specific density and relative dominance of *H. fomes* in the study area was 1248 ha⁻¹ and 26.2%, respectively. Based on the species Iᵥ, *H. fomes* was the principle species in the mangrove community along the oligohaline zone of Sundarbans. Similarly, on the basis of relative dominance, *A. officinalis* and *H. fomes* were considered for carbon stock estimation in their respective above-ground structures. These species constituted 37.2% and 16.0% of above-ground biomass of the mangroves in the study area, respectively. Structural features of the mangrove community are presented in Table 2. The complexity index (Iₙ) ranged from 1.7 to 29.8. The high value of the complexity index (Iₙ = 24.8–29.8) for plots 3–5 in the Ghagramari and Karamjol areas indicates the especially high density of the stand, higher basal area, and greater number of species occurring in these areas. The lowest complexity occurred in the Dhangmari area because of its lower basal area and fewer species.

Simpson’s index (S) measures the probability that two individuals randomly selected from a sample will belong to the same species, where 0 represents infinite diversity and

| Species          | Specific density (n ha⁻¹) | Basal area (m² ha⁻¹) | Relative density (%) | Relative frequency (%) | Relative dominance (%) | Importance value Iᵥ |
|------------------|---------------------------|----------------------|----------------------|-----------------------|------------------------|---------------------|
| *Heritiera fomes*| 1247.6                    | 5.98                 | 53.8                 | 26.1                  | 26.2                   | 106.1               |
| *Excoecaria agallocha* | 533.3                   | 2.33                 | 23.0                 | 26.1                  | 10.2                   | 59.3                |
| *Avicennia officinalis* | 109.5                  | 8.33                 | 4.7                  | 13.0                  | 36.5                   | 54.3                |
| *Xylocarpus mekongensis* | 228.6                  | 2.83                 | 9.9                  | 17.4                  | 12.4                   | 39.6                |
| *Bruguiera sexangula* | 176.2                   | 3.32                 | 7.6                  | 13.0                  | 14.5                   | 35.2                |
| *Aglaya cucullata*  | 23.8                     | 0.04                 | 1.0                  | 4.4                   | 0.2                    | 5.6                 |
The mean above-ground biomass of the mangrove stands was 153.7 ± 40.8 Mg ha\(^{-1}\). The total above-ground biomass ranged from 51.2 Mg ha\(^{-1}\) (plot 6; Dhangmari area) to 314.6 Mg ha\(^{-1}\) (plot 1; Dhangmari area). The mean below-ground biomass of the studied stands was 82.3 ± 19.6 Mg ha\(^{-1}\). The total below-ground biomass ranged from 12.9 Mg ha\(^{-1}\) (plot 6; Dhangmari area) to 141.3 Mg ha\(^{-1}\) (plot 5; Karamjol area). Mean above-ground, below-ground, and total biomass carbon (TBC) of the studied area was 76.8 ± 20.4, 41.1 ± 9.8, and 118.0 ± 29.5 Mg ha\(^{-1}\), respectively (Table 3). The TBC stock was highest in plot 5 (227.9 Mg ha\(^{-1}\)), which was also located in Karamjol area of Sundarbans mangrove forest.

The mangrove forest along the oligohaline zone was dominated by a large number of small trees. Large trees were rare. Figure 1 shows the typical diameter class distribution of mangrove trees in the study area that showed a reverse J-shaped curve with only 27.6% of trees exceeding 10 cm DBH. The largest tree in the studied mangrove area was A. officinalis with a DBH of 56.6 cm and height of 29.5 m, and the second largest tree was H. fomes with DBH of 30 cm and height of 29.9 m. The largest total basal area (34.2 m\(^2\) ha\(^{-1}\)) occurred in the H. fomes—X. mekongensis–A. officinalis dominated community and the smallest basal area (5.1 m\(^2\) ha\(^{-1}\)) occurred in the E. agallocha–H. fomes community in the Karamjol and Dhangmari areas of the Sundarbans, respectively.

To explore the contributions of species in carbon stocking, we calculated the species wise carbon contents in Figure 2a. Figure 2b also shows the species wise number of individuals per hectare. The order of species wise carbon stock in the TBC including above-ground and below-ground biomass carbon was A. officinalis > H. fomes > B. sexangula > X. mekongensis > E. agallocha > A. cucullata. Avicennia officinalis contributed the most to the TBC, while H. fomes was the second highest contributor of carbon accumulation in the Sundarbans mangrove community. It is important to note that A. officinalis constituted only 5% of the total number of individuals, but contributed more than 38% to the TBC. On the other hand, H. fomes constituted more than 55% to the mangrove stands in tree number, but contributed less than 36% to the TBC in the mangrove stands. This is because very large A. officinalis trees were found at scattered locations throughout the study area.

Figure 3 shows the above-ground and below-ground carbon pools assessed by diameter class distribution of different mangrove species in the study area. This reveals the important role of large trees in determining biomass carbon stock in the study area. Individuals of different mangrove species having DBH ≥ 9.99 cm constituted more than 72% in the study plot but contributed less in above-ground and below-ground biomass carbon accumulation representing only 17.4% above-ground carbon mass and 11.8% below-ground carbon mass, respectively. While trees with diameter of 10–56 cm constituted only 28% in number, but had high contributions to above-ground and below-ground biomass carbon accumulation, representing 82.6% of above-ground carbon mass and 88.2% of below-ground carbon mass, respectively.

### Table 2. Stand structure of mangrove communities within the oligohaline zone of Sundarbans, Bangladesh.

| Plot no. | Location   | Number of species | Density (ha\(^{-1}\)) | Total basal area (m\(^2\) ha\(^{-1}\)) | Mean H (m) | Mean DBH (cm) | Complexity index |
|----------|------------|-------------------|-----------------------|----------------------------------------|------------|--------------|------------------|
| 1        | Dhangmari  | 3                 | 4800                  | 16.0                                   | 5.7±0.3    | 5.2±0.6       | 13.2             |
| 2        | Ghagramari | 4                 | 2350                  | 22.9                                   | 7.4±0.4    | 8.4±0.8       | 15.9             |
| 3        | Ghagramari | 5                 | 3450                  | 24.2                                   | 6.6±0.4    | 7.4±0.5       | 27.6             |
| 4        | Karamjol   | 4                 | 1925                  | 29.5                                   | 10.9±0.9   | 11.2±1.0      | 24.8             |
| 5        | Karamjol   | 5                 | 1150                  | 34.2                                   | 15.1±1.4   | 14.8±1.9      | 29.8             |
| 6        | Dhangmari  | 2                 | 2100                  | 5.1                                    | 7.9±0.3    | 4.9±0.3       | 1.7              |
| Mean     |            | 3.8 ± 0.5         | 2629 ± 530            | 22.0 ± 4.2                             | 8.9 ± 1.4  | 8.7±1.5       | 18.8±4.3         |

### Table 3. Tree diversity parameters in mangrove communities within the oligohaline zone of Sundarbans, Bangladesh.

| Site       | Margalef index | Diversity Shannon-Weiner index | Simpson index | Evenness Pilou index |
|------------|----------------|-------------------------------|---------------|----------------------|
| Dhangmari  | 3.93±0.46      | 1.49±0.08                     | 0.74±0.02     | 0.88±0.00            |
| Ghagramari | 4.01±0.52      | 0.96±0.23                     | 0.49±0.17     | 0.57±0.16            |
| Karamjol   | 1.94±0.46      | 0.84±0.37                     | 0.51±0.01     | 0.88±0.07            |
| Mean       | 3.30±0.68      | 1.10±0.20                     | 0.58±0.08     | 0.71±0.09            |
Discussion

Stand structure

Stand density of the oligohaline zone of Sundarbans mangrove forest (2629 ha$^{-1}$) was comparable to that of mature riverine mangrove ecosystems or mixed mangrove stands (3310–917 ha$^{-1}$) in French Guiana (Fromard et al. 1998) where higher density at the pioneer stage than at the mature stage was found. Our observations indicated higher densities than the findings of Haron (1981) and Aksornkoae (1993), who reported mean density of a mature mangrove stand of 1343 stems ha$^{-1}$ in Matang mangrove forest, Malaysia, and of 812 stems ha$^{-1}$ in Ranong, Indonesia. In the present study we observed that communities with small trees had high density, while communities with large trees had lower density (Table 2; Figure 1). This result indicates competition for resources within the stands, which creates size variation and density-dependent mortality or self-thinning. Our findings agree with the summarization by Kamara et al. (2014) who reported that density-dependent mortality or self-thinning is a natural phenomenon in overcrowded mangrove stands on Okinawa Island, Japan. This is also in agreement with Fromard et al. (1998) who suggested that density was the most discriminating factor for early development stage of mangroves: a young stand matures by decreasing the number of individuals.

Six true mangrove species under five families have been recorded from the study area. *Heritiera fomes*, a dominant mangrove species in the study area, had the highest importance value ($I_v = 106.1$) among all species. The second most
dominant species was *E. agallocha* (*I* *v* = 59.3), which had an importance value higher than that of the dominant mangrove species of the Andaman Islands, India (88.4 and 48.7, respectively; Padalia et al. 2004). The *I* *v* for the dominant species was also higher than that reported for the dominant species (*I* *v* = 69.3 – 61.1) in mangroves of northwestern coast of Sri Lanka (Perera et al. 2013). On the other hand, the present value of *I* *v* for the dominant species (*I* *v* = 44.6 – 277.8) was lower than that reported for *Avicennia marina* (Forsk.). Vierh dominants stands on Lothian Island, Sundarbans Biosphere Reserve, West Bengal, India (Joshi and Ghose 2014). With a high value of relative density (53.8%), relative frequency (26.1%), and relative dominance (26.2%), *H. fomes* and *E. agallocha* were the dominant species in the mangrove communities along the oligohaline zone of Sundarbans mangrove forest, Bangladesh. Moreover, the mean structural complexity of the present study area was 18.8 ± 4.3, which was higher than the estuarine mangroves on the northwestern coast of Sri Lanka (15.1 ± 7.0; Amarasinghe and Balasubramaniam 1992). In the present study area, the mangroves grow on relatively flat topographic slopes and the frequent tidal flushing provides a favorable nutrient balance. These conditions may be suitable to support a greater number of species and more complex community structures.

Shannon-Weiner (*H*) and Margalef (*R*) species diversity values were 1.10 and 3.30, respectively, in the oligohaline zone of Sundarbans, and were higher than those of 1.07 and 1.67, respectively, reported for the mangrove stands on the Andaman Islands, India (Padalia et al. 2004). Diversity index values in the present study were higher than those in the undisturbed area of Semporna mangrove forest, Malaysia (*H* = 0.711; Wah et al. 2011). The forest structures of the mangrove stands in the present study were simple and largely composed of small trees, in agreement with Joshi and Ghose’s (2014) finding that natural vegetation shows reverse J-shaped population structures with expanding or developing populations. The findings of the present study show that the mangrove forest along the oligohaline zone of SRF is diverse in terms of species composition and abundance, as revealed by various indices of diversity.

**Biomass and carbon storage**

The present study showed that the mean above-ground biomass (153.7 Mg ha\(^{-1}\)) was much higher than that reported for a subtropical mangrove forest on Ishigaki Island, southern Japan (97.6 Mg ha\(^{-1}\); Suzuki and Tagawa 1983), *Avicennia marina* (Forsk.) Vierh dominated mangrove in Sofala Bay, Mozambique (134.6 Mg ha\(^{-1}\); Sitoe et al. 2014), and *R. mangle* dominated fringe mangrove forest at Florida, USA (26.1 Mg ha\(^{-1}\); Ross et al. 2001). This value was also higher than the mean range of above-ground biomass (89.7–42.9 Mg ha\(^{-1}\)) for *B. parviflora* (76.0–279.0 Mg ha\(^{-1}\)) for *B. sexangula*, and (40.7 Mg ha\(^{-1}\)) for *R. apiculata* dominated mangrove forest in East Sumatra, Indonesia (Kusmana et al. 1992). The present value of above-ground biomass was lower than the findings of Putz and Chan (1986) who reported the above-ground biomass of a mature *Rhizophora–Bruguiera* dominated mangrove forest in Malaysia of 270 – 460 Mg ha\(^{-1}\). Above-ground biomass production in the present study was almost identical to that (159 Mg ha\(^{-1}\)) of *Rhizophora apiculata* Bl. dominated mangrove forest in southern Thailand (Christensen 1978). Compared to the previous research, the present study indicates that biomass productivity of the mangrove species in SRF is relatively high among mangrove forests in tropical and subtropical areas.

Accumulation of mean above-ground biomass carbon of the studied area was 76.8 Mg ha\(^{-1}\). Similar observations were recorded in secondary mangrove forest in southern Thailand (92.1 Mg ha\(^{-1}\); Komiyama et al. 2000). The range of the above-ground biomass carbon of the present study (25.6–157.3 Mg ha\(^{-1}\)) was higher than that recorded for mangrove forests in the Sundarbans, India: 22.1–111.4 Mg ha\(^{-1}\) (Mitra et al. 2011) and 34.6–90.8 Mg ha\(^{-1}\) (Ray et al. 2011). The present mean value of above-ground biomass carbon was lower than that recorded on mangroves of Micronesia (104.4 Mg ha\(^{-1}\); Kauffman et al. 2011). Mean biomass carbon of the studied mangroves (118.0 Mg ha\(^{-1}\)) was higher than that recorded on mangroves in Sofala Bay, Mozambique (58.6 Mg ha\(^{-1}\); Sitoe et al. 2014), in China (84.6 Mg ha\(^{-1}\); Liu et al. 2014), and in Yingulu Bay, Guangdong province in south China (86 Mg ha\(^{-1}\); Wang et al. 2013). Tree biomass carbon was highly variable in the present study sites (Table 4), ranging from 32.0–46.21 Mg ha\(^{-1}\) in Dhangmari to 156.4–227.9 Mg ha\(^{-1}\) in Karamjol. It is interesting to note that carbon storage was much lower in Dhangmari where the stem density was much higher than Karamjol. In addition to this, the mangrove stands of Dhangmari are younger than those in other areas in the Bangladeshi Sundarbans.

This is the first study to report the species wise contribution to the TBC of the Sundarbans mangrove forest, Bangladesh. Based on the information presented here, we can identify the carbon storage performances of the different mangrove species in the SRF. For example, *A. officinalis* was lower in species richness compared to *H. fomes*, but played a major role in carbon storage in the Sundarbans. Similar findings were also reported by Ruiz-Jaen and Potvin (2011), who reported that the dominance of a given species alone is not a strong determinant for tree carbon storage. We conclude that tree carbon storage in the studied mangrove stands could not be explained by species richness. *Avicennia officinalis* was fifth in species ranking based on species dominance, with only a few individual trees occurring at scattered locations. However, being very large trees they contributed the most to carbon storage in the stands.

**Conclusion**

It may be concluded that biomass and carbon accumulation of mangrove species vary with different species and size class. Carbon storage is not dependent on dominance of the species, nor does it vary with individual basal area of the species. The potential yield of carbon storage within the oligohaline

### Table 4. Biomass carbon accumulation (Mg ha\(^{-1}\)) in mangrove communities within the oligohaline zone of Sundarbans, Bangladesh.

| Plot no. | Above-ground biomass carbon (Mg ha\(^{-1}\)) | Below-ground biomass carbon (Mg ha\(^{-1}\)) | Total biomass carbon (Mg ha\(^{-1}\)) |
|----------|-------------------------------------------|------------------------------------------|----------------------------------|
| 1        | 26.08                                     | 20.14                                    | 46.21                           |
| 2        | 78.55                                     | 40.41                                    | 118.96                          |
| 3        | 69.27                                     | 57.30                                    | 126.37                          |
| 4        | 104.25                                    | 52.14                                    | 156.39                          |
| 5        | 157.29                                    | 70.63                                    | 227.92                          |
| 6        | 25.58                                     | 6.43                                     | 32.01                           |
| Mean     | 76.83 ± 20.4 | 41.14 ± 9.82 | 117.98 ± 29.54                  |
zone of SRF in Bangladesh should be assessed by direct estimation of the present carbon stocks.

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Disclosure statement

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