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STAND STRUCTURE AND FINE ROOT PRODUCTION WITH THEIR BENEFACTION TO CARBON STORAGE IN THE SUNDARBANS MANGROVE FOREST

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Abstract

The quantification of fine root production (FRP) and fine root biomass (FRB) in mangrove ecosystem is of utmost importance in gaining insights into ecosystem dynamics. However, these aspects have received limited attention in mangrove forests, primarily due to the considerable time and labor required for accurate assessment. Therefore, our study aims to estimate FRP and FRB stocks in the Sundarbans mangrove forest in Bangladesh, specifically focusing on two distinct saline zones: oligohaline and mesohaline. To accomplish our objectives, we employed sequential soil coring and long-term ingrowth core methods to collect soil samples from 20 study plots, each covering an area of 100 square meters. Additionally, we assessed the forest structure by measuring the tree height and diameter at breast height. Our findings revealed that the mean FRB and FRP across the study area were 12.7 ± 1.1 Mg ha^{-1} and 2.3 ± 0.1 Mg ha^{-1} yr^{-1}, respectively. Notably, the oligohaline zone, characterized by lower salinity levels, exhibited higher FRB stocks and FRP compared to the mesohaline zone. Our analysis showed that FRP in the diameter class of 1-2 mm surpassed that of the 0.5-1 mm and $\leq$0.5 mm classes. In terms of organic carbon, the mean above-ground, below-ground, and total organic carbon were 93.7 ± 18.3, 48.4 ± 7.6, and 142 ± 26 Mg C ha^{-1}, respectively. Through species importance value (Iv) analysis, we identified *Excoecaria agallocha* as the dominant species in the oligohaline zone, while *Sonneratia apetala* exhibited the highest Iv value in the mesohaline area. *Heritiera fomes* emerged as the primary contributor to total organic carbon, particularly in the oligohaline zone, whereas *S. apetala* contributed the most organic carbon in the mesohaline zone. These findings emphasize the importance of protecting and conserving mangrove ecosystems as valuable contributors to global carbon dynamics due to their higher fine root production and their contribution to carbon stocks.

Keywords: Mangroves, Stand structures, Organic carbon, Fine roots, Ingrowth core, Root production.

Introduction

The relationship between terrestrial ecosystems and the atmosphere is well documented, with numerous studies highlighting the effects of this interaction on the concentration of CO_2 (Heimann et al. 1989; Osawa & Aizawa 2012). To anticipate future changes in the global climate system, it is crucial to gain a comprehensive understanding of carbon dynamics within terrestrial ecosystems (Heimann & Reichstein 2008; Osawa & Aizawa 2012). The movement of assimilates to belowground plant organs is an indispensable aspect of net primary production (NPP) in the terrestrial ecosystem, which helps to originate fine roots and sustain mycorrhizae (Osawa & Aizawa 2012). Mangrove habitats possess unrivaled productivity and are concurrently exposed to significant risks stemming from natural factors and human-induced pressures (Roy & Krishnan, 2005; Nagarajan et al., 2008). The high productivity of mangrove ecosystems can be attributed to their high net productivity and relatively low soil respiration rates, highlighting their significance in carbon sequestration and overall ecosystem functioning (Poungparn et al. 2012; Poungparn et al. 2016). Numerous studies on biomass and productivity in mangroves worldwide primarily aimed to provide crucial insights for understanding ecosystem functioning and thereafter management (Kamruzzaman et al. 2018, Ahmed et al. 2023). Furthermore, the mangroves' root systems produce enormous amounts of biomass, and it is essential to clarify the mangrove root system in the context of carbon dynamics (Poungparn et al. 2016).

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Fine roots, with a diameter of ≤ 2 mm, serve as vital conduits for plant water and nutrient uptake, exerting significant influence on carbon dynamics within forests soil (Trumbore & Gaudinski 2003, Xiao et al. 2008). Fine root production (FRP) and fine root biomass (FRB) are critical in understanding the ecological process that occurs in the mangroves (Adame et al. 2014), as FRP is associated with below-ground carbon stocks and sequestration (Alongi 2011). Nutrients availability in mangroves controls the formation of fine roots (Mckee et al. 2007; Adame et al. 2014). In situations of nutrient limitation, mangroves have the ability to allocate a significant proportion up to 60% of their biomass towards the production of roots. This remarkable allocation strategy enables mangroves to sustain their productivity, surpassing above-ground productivity, as fine roots are continually renewed (Helmissari et al., 2002; Naidoo, 2009; Ahmed et al., 2021). The root biomass and productivity of mangroves often fluctuate with interstitial salinity (Krauss et al. 2013). However, exemplary root contribution has not been adequately considered in the evaluation of net primary productivity in the natural ecosystem because of the intricacy of its exact pools and fluxes estimated using recognized instruments and methodologies (Hendrick & Pregitzer 1993; Lopez et al. 2001; Osawa & Aizawa 2012). The assessment of fine root dynamics in natural environments has been the subject of extensive research, resulting in the proposal of various methods. Sequential soil coring (SSC) and ingrowth cores (IC) are among the significant approaches suggested for studying fine roots and their associated processes (Castaneda-Moya et al. 2011; Ostonen et al. 2005; Yang et al. 2010).

The Sundarbans, located in the Ganges-Brahmaputra delta, is the most extensive contiguous patch of mangrove forest around the globe (Siddique et al. 2021). This immense forest spans an area of 6,017 km^2 in Bangladesh, with geographical coordinates ranging from 21^o 30’-22^o 30’ N and 89·00 ^{o}-89^o55’E (Hossain et al. 2015). The Sundarbans are categorized into three separate eco-salinity zones, such as fresh water (oligohaline), medium saline water (mesohaline), and high saline water (polyhaline) zones (Chaffey et al. 1985). According to Ahmed et al. (2011), the geographical distribution of plant communities might be a consequence of changes in salinity.

This research focused on estimating FRB and FRP in the Oligohaline and Mesohaline zones of the Sundarbans mangrove forest (SMF), utilizing the SSC and IC methods, respectively. Additionally, we assessed the structural characteristics, above and below-ground organic carbon production, and the contribution of fine roots to carbon storage in the SMF, providing insights into their role in this forest ecosystem.

Materials and Method

Study site

SMF is residing in a warm, humid tropical environment with an annual temperature that ranges between 21^oC and 30 °C, the typical relative yearly humidity in this region fluctuates from 70% to 80%, and the mean annual precipitation varies between 1,640 mm and 2,000 mm (Rahman & Asaduzzaman 2010; Aziz & Paul 2015). To collect data, we established 20 (10 m × 10 m) plots, ten plots in each zone, covering an area of 2,000 m^2 (Figure 1).

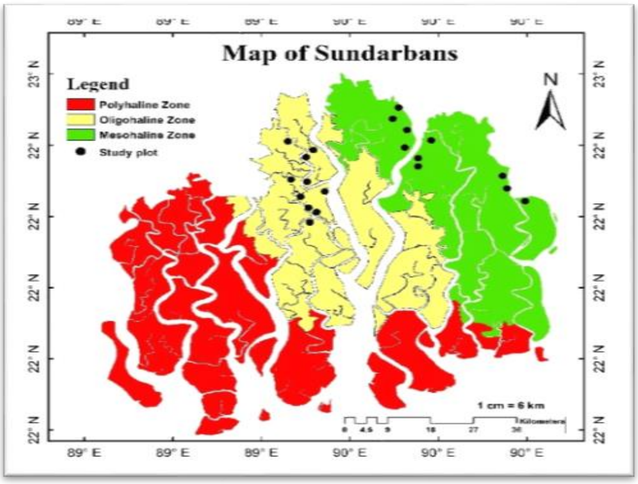

Figure 1. Location of the study area. The black circle denotes the plot area.

From the field observation, it was found that most of the tree damages occurred during storms and soil erosion in the closest periphery of the rivers, so in order to minimize potential harm from the storms and soil erosion, it was needed to place all study plots around 200 m from the coastline.

Forest composition and structure

In the plots, we observed 12 mangrove species. To assess the structural features of the forest and their influence on carbon storage, we evaluated the species composition, tree density, and the basal area of all trees by measuring the diameter at breast height (DBH) with at least 1.8 cm. It has been widely acknowledged that mangrove DBH and tree height significantly determines their carbon storage capacity (Cintron & Novelli, 1984).

Above-Ground and Below-Ground Organic carbon Stocks Estimation

Despite the existence of allometric equations that establish a relationship between DBH and height for various mangrove species across the globe, the production of biomass is determined by the interaction of the edaphic, climatic, and topographic factors of the defined location and the species available in the ecosystem (Kamruzzaman et al. 2018). In this study, we carefully calculated the biomass for each of the examined mangrove species found in our research area using the above-ground biomass (AGB) and below-ground biomass (BGB) equations listed below.

$$AGB = 0.0673\ (WD * D^2 * H)^{0.976} \qquad \text{(Chave et al., 2014)}$$

$$BGE = (0.199 * WD^{0.899} * D^{2.22}) \qquad \text{(Komiyama et al., 2005)}$$

Where AGB = aboveground biomass, BGB = belowground biomass, WD = wood density, D = DBH, and H= height. The wood density data was taken from the Global Wood Density Database, as proposed by Chave et al. (2009). Biomass was then multiplied by 0.47 in order to convert tree biomass to carbon mass as followed by Gifford (2000).

Estimation of Fine Root Production and Fine Root Biomass

The ingrowth core technique, based on the work of Neil (1992) and Hendricks et al. (2006), was utilized to examine fine root production. Plastic mesh cores with a diameter of 4 cm and length of 30 cm, filled with root-free soil (collected from the riverside), were installed vertically (up to 30 cm) into the forest soil. The long-term ingrowth cores, consisting of 160 cores collected at intervals of ~2, 4, 6, and 12 months, were carefully rinsed to isolate manually (based on color and texture) and categorize the fine roots based on diameter and viability. Fine roots were divided into three diameter classes: class-1 (1-2 mm), class-2 (0.5-1 mm), and class-3 (≤ 0.5 mm), and oven dried for 72 hours at 70°C (Van Do et al. 2016). After that, the biomass of dried fine roots, along with root necromass, were used as parameters to calculate the production of fine roots. A simplified decision matrix method developed by Fairley (1985) was used to calculate the FRP during each study period. The production of fine roots in the two different salinity regimes was expressed as a mega gram per hectare per year (Mg ha^{-1} yr^{-1}).

To assess the FRB stocks, we collected 8 soil cores (total of 160) (by using stainless steel corer: 4 cm diameter, 50 cm length) from each plot and categorized them into three sub-soil depths, such as 0-10 cm, 11-20 cm, and 21-30 cm. Living and dead fine roots were sorted and separated into three diameter classes as described above. The roots were then dried at 70°C, and the FRB was converted to mega grams per hectare (Mg ha^{-1}). After that, the fine root biomass was converted into the fine root organic carbon (FROC), and the value was expressed as Mg C ha^{1}.

Statistical Analyses

To investigate variations in FRP and FRB across different soil depths, a two-way analysis of variance (ANOVA) was conducted. The dependent variables were FRP and FRB, while the independent variables were salinity zones and soil depths. Significant differences were tested, and pairwise comparisons were performed using the Bonferroni post hoc test. Statistical analyses were conducted using SPSS version 23 and Microsoft Excel 2021 software, and figures were created using R programming software version 4.2.1 (R Core Team, 2022).

Results

Forest Structure

We observed 12 species in two salinity zones of the SMF. *Excoecaria agallocha* predominates in the oligohaline zone, providing a critical value index (Iv = 122.8) (Table 1). Besides, the Iv value for *Avicennia officinalis*, *Bruguiera sexangula*, *Sonneratia apetala*, *Xylocarpus mekongensis*, *Aegieceras corniculatam*, *Cynametra ramiflora*, *Heritiera fomes*, *Sonneratia caseolaris*, *Rhizophora apiculata* were 21.8, 13.3, 7.0, 22.6, 6.6, 6.6, 91.2, 7.0 and 3.5 respectively (Table 1). *S. apetala* exhibited the highest Iv (99.8) value of any other species in the mesohaline zone indicating that *S. apetala* was the key species in the ecosystem (Table 1). In the mesohaline area, *X. granatum* and *R. apiculata* exhibit the lower I$_V$ value of only 5.6 and 6.5 respectively. On the other hand, *A. officinalis*, *S. caseolaris*, *E. agallocha*, *B. sexangula*, *A. corniculatum*, *Lumnitzera racemosa*, *X. mekongensis,* and *H. fomes* carried 23.4, 10, 88.3, 14.0, 12.2, 11.4, 18.8 and 10.0 correspondingly (Table 1). *E. agallocha* occupied an area with a specific density of 11,100 ha^{-1} and a relative dominance of 47.3% in the oligohaline zone. Depending on specific density, relative dominance, and species Iv, *E. agallocha* was the principal species in the community of mangroves within the oligohaline zone of the SMF. Similar to this, *S. apetala* had a specific density of 3400 ha^{-1} and a relative dominance of 64.7% in the mesohaline zone.

The mean specific density in the oligohaline and mesohaline zones was 2140 ha^{-1} and 1536.3 ha$^{-1,}$ respectively (Table 2). Additionally, the mean dbh in oligohaline and mesohaline were 11.3 cm and 13.6 cm, respectively (Table 2). Comparing these two salinity zones, the mean height and dbh in oligohaline were lower than that in the mesohaline zone. In contrast, the mean specific density was higher in the oligohaline zone (Table 2) indicating that numerous numbers of small trees dominated the oligohaline zone. On the other hand, the mesohaline zone was occupied by trees that were larger than those observed in the oligohaline zone. Our study also reported that larger trees were rare in both locations.

Table 1. Structural composition of mangrove communities between the Oligohaline & Mesohaline zones of Sundarbans, Bangladesh.

Zone	Species	Specific density (n ha^{-1})	Basal area (m^2 ha^{-1})	Relative density %	Relative dominance %	Relative frequency %	IV
Oligohaline	AVOF	500	3.2	2.34	6.2	13.2	21.8
	EXAG	11100	13.6	51.9	47.3	23.7	122.8
	BRSE	400	0.5	1.87	0.8	10.5	13.3
	SONAP	200	1	0.93	0.8	5.3	7.0
	XYME	900	2.6	4.21	5.0	13.2	22.4
	AECO	200	0.5	1.0	0.4	5.3	6.6
	CYRA	200	0.5	1.0	0.4	5.3	6.6
	HEFO	7600	16.3	35.5	38.0	15.8	91.2
	SONCA	200	1	0.94	0.8	5.3	7.0
	RHAP	100	1	0.5	0.4	2.6	3.5
Mesohaline	AVOF	800	3.5	4.7	5.9	12.8	23.4
	SONCA	300	2.2	1.8	1.9	6.4	10.0
	XYGR	200	100.0	1.2	0.1	4.3	5.6
	EXAG	8400	6.1	49.7	17.3	21.3	88.3
	RHAP	200	1.8	1.2	1.0	4.3	6.5
	BRSE	900	2.8	5.3	2.3	6.4	14.0
	SONAP	3400	32.7	20.1	64.7	14.9	99.8
	AECO	800	1.3	4.7	1.1	6.4	12.2
	LURA	400	0.5	2.4	0.5	8.5	11.4
	XYME	900	2.0	5.3	2.8	10.6	18.8
	HEFO	600	3.9	3.6	2.2	4.3	10.0

HEFO= *Heritiera fomes*, EXAG= *Excoecaria agallocha*, BRSE= *Bruguiera sexangula*, XYME= *Xylocarpus mekongensis*, AVOI= *Avicennia officinalis*, SONAP= *Sonneratia apetala*, SONCA= *Sonneratia caseolaris*, CYRA= *Cynametra ramiflora*, AECO= *Aegiceras corniculatum*, RHAP= *Rhizophora apiculata*, LURA= *Lumnitzera racemosa*, XYGR= *Xylocarpus granatum.*

Table 2. Stand structure of mangrove communities between two different salinity zones of the Sundarbans mangrove forest, Bangladesh.

Salinity zone	Density (*n* ha^{-1})	Basal area (m^2 ha^{-1})	Mean *H* (m)	Mean *DBH* (cm)
Oligohaline	2140 ± 252.6	25.7 ± 3.2	8.5 ± 0.2	11.3 ± 0.5
Mesohaline	1536.3 ± 179.2	35.3 ± 5.9	10.0 ± 0.6	13.6 ± 1.07
Mean	1838.15 ± 215.9	30.5 ± 4.5	9.25 ± 0.4	12.45 ± 0.8

Biomass and carbon stocks

The mean AGB of the Sundarbans mangrove at oligohaline and mesohaline zones was 187.3 ± 36.6 Mg ha^{-1} (Table 3). The total AGB varied from 135.0 Mg ha^{-1} in the oligohaline zone and 239.6 Mg ha^{-1} in the mesohaline zone. Additionally, the mean BGB of the studied stands was 96.8 Mg ha^{-1}, with the total BGB ranging from 87.9 Mg ha^{-1} in the oligohaline zone to 105.6 Mg ha^{-1} in the mesohaline zone. The mean values for above-ground (AGC), below-ground (BGC), and total organic carbon stocks (TOC) for the two different saline zones were 93.7 ± 18.3, 48.4 ± 7.6, and 142.1 ± 26.0 Mg C ha^{-1}, respectively (Table 3).

Table 3. Accumulation of biomass (Mg ha^{-1}) and organic carbon (Mg C ha^{-1}) in mangrove communities within two different salinity zones of Sundarbans, Bangladesh.

Salinity zone	**Aboveground Biomass (Carbon)**	**Belowground Biomass (Carbon)**	**Total Biomass (Carbon)**
Oligohaline	134.9 ± 23.2 (67.5 ± 11.6)	87.9 ± 13.8 (43.9 ± 6.9)	222.9 ± 37.4 (111.4 ± 18.7)
Mesohaline	239.6 ± 50.02 (119.8 ± 25.01)	105.6 ± 16.6 (52.8 ± 8.3)	345.4 ± 66.4 (172.7 ± 33.2)
Mean	187.3 ± 36.6 (93.7 ± 18.3)	96.8 ± 15.2 (48.4 ± 7.6)	284.1 ± 52 (142.1 ± 26)

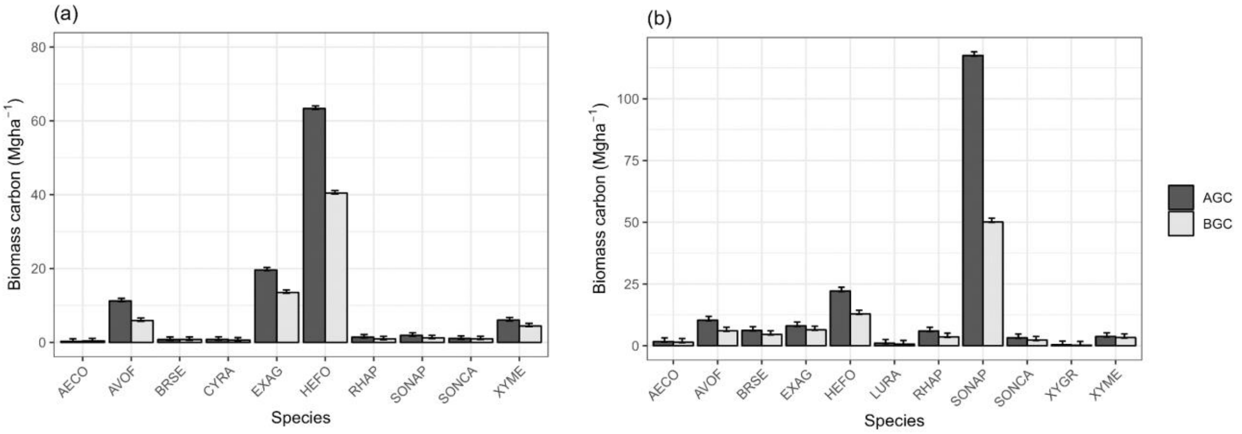

Figure 2. Species-wise contribution to organic carbon stocks (AGC= above-ground organic carbon; BGC= below-ground organic carbon). **(a)** Oligohaline zone; (**b)** Mesohaline zone area.

Notably, the highest TOC stocks were recorded in the mesohaline zone of the Sundarbans mangrove forest. In the oligohaline zone, the sequence of species-wise carbon stock in the TOC comprising both AGB and BGB carbon was *H. fomes* > *E. agallocha* > *A. officinalis* > *X. mekongensis* > *S. apetala* > *R. apiculata* > *S. caseolaris* > *B. sexangular* > *C. ramiflora* > *A. corniculatum*. *H. fomes* contributed substantially to the TOC, followed by *E. agallocha* and *A. officinalis* in the oligohaline zone, as shown in Figure 2(a). Furthermore, in the mesohaline zone, *S. apetala* received the top position in carbon stock, whereas *H. fomes* also ranked in the second position, as depicted in Figure 2(b). Within the oligohaline zone, *H. fomes* made up 36% of the total number of individuals and contributed the highest proportion of the TOC, while *E. agallocha* represented 52%. Interestingly, *A. officinalis* constituted a lower percentage of the total number of individuals, but it contributed almost the same amount to the TOC as *E. agallocha*. This can be attributed to the presence of very large *A. officinalis* trees located sparsely throughout the oligohaline zone. The species-wise carbon storage in the Mesohaline zone was *S. apetala* > *H. fomes*> *A. officinalis*> *E. agallocha*> *B. sexangula*> *R. apiculata*> *X. mekongensis*> *S. caseolaris*> *A. corniculatum*> *L. racemosa*> *X. granatum*.

Fine Root Production

The mean FRPs in our study were 2.1 Mg ha^{-1}yr^{-1} in the mesohaline zone and 2.4 Mg ha^{-1}yr^{-1} in the oligohaline zone. The FRP in the oligohaline zone was higher compared to the mesohaline zone. The FRP tends to decline as soil depth increases (Figure 3). Within the three diameter classes of fine roots, the larger diameter class (1-2 mm) had the highest production (Table 4). Additionally, we observed significant ($p<0.05$) differences in the (1-2 mm and 0.5-1 mm) diameter classes, which varied between the salinity zones. Besides, the production of the smallest root diameter, especially (≤0.5mm) was significantly lower and there was no significant ($p>0.05$) difference in terms of root production between the oligohaline and mesohaline zones. Overall, the highest production of fine root was found in the top layer of soil depth 0-10 cm than the bottom layer of soil depths 10-20 cm, and 20-30 cm respectively (Figure 3). Notably, there was no significant ($p>0.05$) dissimilarity observed for FRP across different soil depths.

Fine Root Biomass and Organic carbon

The mean FRB exhibited a range of 10.5 Mg ha^{-1} in the mesohaline zone to 14.8 Mg ha^{-1} in the oligohaline zone, while the mean value of FRB carbon varied from 5.2 Mg C ha^{-1} to 7.4 Mg C ha^{-1}, respectively. Our overall mean value of FRB was 12.7 ± 1.1, and the mean FRB carbon was observed to be 6.3 ± 0.3 Mg ha^{-1} in the Sundarbans, Bangladesh. The FRB demonstrated a distinct decrease as the soil depth increased, especially for the more extensive root diameter class, between the two different saline zones (Table 4). No significant ($p>0.05$) differences were detected in the FRB across different soil depths. The fine roots with the largest diameter (1-2 mm) classes showed significant variation ($p<0.05$) between the two different salinity zones. Conversely, the least diameter classes of fine roots, including 0.5-1.0 mm and ≤0.5 mm, did not exhibit any significant ($p>0.05$) differences. The contribution of fine root organic carbon to total organic carbon ranged from 2.8% in the mesohaline zone to 5.3% in the oligohaline zone (Figure 4). On average, fine roots contributed 4% of the total organic carbon. Fine roots accounted for approximately one-eighth of the BGB and roughly one-fifteenth of the AGB in the Sundarbans mangrove forest (Figure 4).

Table 4. Fine Root Biomass and Fine Root Production across the salinity zones based on diameter class and soil depths.

Zone	**Depth (cm)**	**FRP (Mg ha^{-1} yr^{-1})**			**FRB (Mg ha^{-1})**		
		Diameter Class (mm)			Diameter Class (mm)		
		(1-2mm)	(0.5-1mm)	(≤0.5mm)	(1-2mm)	(0.5-1mm)	(≤ 0.5mm)
Oligohaline	0-10	1.5 ± 0.2	0.8 ± 0.1	0.7 ± 0.04	10.2 ± 0.6	5.0 ± 0.2	2.9 ± 0.2
	10-20	1.0 ± 0.1	0.8 ± 0.1	0.5 ± 0.05	8.4 ± 0.5	3.1 ± 0.3	2.9 ± 0.1
	20-30	0.9 ± 0.1	0.7 ± 0.05	0.4 ± 0.03	4.3 ± 0.4	2.8 ± 0.2	2.3 ± 0.1
Mesohaline	0-10	1.3 ± 0.2	0.7 ± 0.1	0.6 ± 0.1	8.7 ± 0.5	3.7 ± 0.2	2.8 ± 0.2
	10-20	0.9 ± 0.1	0.7 ± 0.1	0.5 ± 0.05	6.2 ± 0.4	2.6 ± 0.1	2.6 ± 0.2
	20-30	0.8 ± 0.1	0.50 ± 0.05	0.4 ± 0.04	3.02 ± 0.2	2.4 ± 0.1	2.2 ± 0.1

Figure 4. Illustrating the percentage of contribution level of fine root organic carbon (FROC), above-ground carbon (AGC), and below-ground carbon (BGC) along the different salinity zone in Sundarbans, Bangladesh.

Discussion

Forest Structure

This study showed that the structure of the forest differed across salinity zones. Based on mean dbh and height of the tree, the mesohaline zone has more mature forest than the oligohaline zone. The stand density ranges from 1536.3 ha^{-1} in the mesohaline zone to 2140 ha^{-1} in the oligohaline zone, which is relatively lower when compared to mature riverine mangrove forests (917 - 3310 ha^{-1}) in French Guiana, as claimed by Fromard et al. (1998). Our investigation showed that mangrove communities with small trees had higher densities than those with larger trees (Table 2) indicating that tree densities are lower when mangroves are older which was also evident from a recent study in plantation mangroves of the Bangladesh Delta (Uddin et al., 2022). The most dominant species in the oligohaline zone was *E. agallocha*, which had the highest importance value (I_V=120.2) among all other species. *H. fomes*, the second prevalent species in this zone, with an importance value of I_V=91.2. In contrast, *S. apetala* was the dominant species in the mesohaline zone, with an important value of Iv=99.8, while *E. agallocha* was the second leading species in this zone, consistently occupying 88.3 Iv value. In the Sundarbans study areas, *E. agallocha* and *S. apetala* were identified as the prevalent species, with higher importance values (Iv), surpassing the leading species in the Andaman Islands, India, as reported by Padalia et al. (2004), where their Iv values were 88.4 and 48.7, respectively. Furthermore, the prime species in our study area had a greater Iv value than the prevalent species (I_V=69.3 ~ 61.1) observed in the mangroves along Sri Lanka's northwestern coast (Perera et al. 2013). The current research outcomes showed that the species composition and abundance of the mangrove forests in the two salinity zones are diverse, as demonstrated by various diversity indices. The presence of suitable environmental conditions and balanced nutrition may have contributed to the diverse range of species and complex community structures observed in the Sundarbans mangrove forest (Kamruzzaman et al. 2018).

Biomass and Carbon Accumulation

We found that the mesohaline zone had a greater carbon accumulation compared to the oligohaline zone (Table 3). This difference in carbon storage could be explained by the status of above-ground vegetation. Previous research conducted by Westoby et al. (2002), Klimesˇova´ et al. (2008), and Ahmed et al. (2021) have demonstrated that the size of trees is significantly correlated with carbon stock. In this study, the mean value of AGB was much higher (174.4 Mg ha^{-1}) than the value (97.6 Mg ha^{-1}) of subtropical mangrove forest on Ishigaki Island in southern Japan (Suzuki & Tagawa 1983). The present mean value of the AGB was also higher than that of other mangrove forests such as the fringe mangrove forest (26.1 Mg ha^{-1}) in Florida, USA, which was prevalent by *R. mangle* (Ross et al. 2001); *A. marina* predominated mangrove forest (134.6 Mg ha^{-1}) in Safola Bay, Mozambique (Sitoe et al. 2014); and *K. Obovata* mangrove stand (75.1 Mg ha^{-1}) in Okinawa, Japan (Khan et al. 2007). The present mean AGB value was advanced than the AGB ranges reported for *B. parviflora* (42.9-89.7 Mg ha^{-1}), *B. sexangula* (76.0-279.0 Mg ha^{-1}), and *R. apiculata* (40.7 Mg ha^{-1}) dominated mangrove forests in East Sumatra, Indonesia (Kusmana et al.1992) and also exceeded the results of *R. apiculata* dominated mangrove (159 Mg ha^{-1}) forest in southern Thailand (Christensen 1978).

The AGC ranged from 61.44 to 112.93 Mg C ha^{-1}, which was superior to the mangrove forests in the Sundarbans, India (22.1 to 111.4 Mg ha^{-1}) reported by Mitra et al. (2011), and 34.6 to 90.8 Mg ha^{-1} claimed by Ray et al. (2011). The present total mean organic carbon (135.6 Mg C ha^{-1}) was surpassed the organic carbon values reported for mangroves in other locations, such as the value of 104.4 Mg C ha^{-1} in Micronesia (Kauffman et al. 2011); 58.6 Mg C ha^{-1} in mangroves of Sofala Bay, Mozambique (Sitoe et al., 2014); 84.6 Mg C ha^{-1} in China (Liu et al., 2014); and 86 Mg C ha^{-1} in Yinguluo Bay, Guangdong province, southern China (Wang et al., 2013). Compared to prior research, our current study indicated that the accumulation of biomass of mangrove species in the Sundarbans Reserved Forest was notably higher than in other mangrove forests in tropical and subtropical regions.

Fine Root Biomass and Organic carbon

The mangrove forest species exhibit a significant concentration of fine roots in the upper 30 cm of soil, indicating an adaptive response to optimize water uptake and nutrient absorption in accordance with physiological requirements (Tomlinson, 1986). Our present study revealed that the oligohaline zone of the SMF exhibited a higher value of FRB compared to the mesohaline zone (Fig. 3). The present mean value of FRB (12.7 Mg ha^{-1}) was higher compared to boreal forest (6.0 Mg ha^{-1}), tropical evergreen forest (5.7 Mg ha^{-1}), and tropical deciduous forests (5.7 Mg ha^{-1}) founded by Jackson et al. (1997), and also higher from boreal forest (5.3 Mg ha^{-1}), temperate forest (7.8 Mg ha^{-1}), and tropical forests (7.8 Mg ha^{-1}) reported by Finer et al. (2011). Our findings were consistent with the findings of Adame et al. (2017) that the observed difference in the FRB stocks could potentially be ascribed to methodological inconsistencies or variations in the collected samples especially sequential soil coring method may be underestimate the fine root biomass of mangroves. Perhaps fine roots made up almost one-sixteenth of the AGB and approximately one-ninth of the AGB, as illustrated in Fig. 4. As a result, fine roots substantially contributed to the accumulation of carbon. Furthermore, the fine roots indicated an essential ecosystem function in influencing the climate by sequestering CO_2 from the atmosphere, which was aligned to the previous studies (Ahmed et al. 2021).

Fine Root Production (FRP)

The oligohaline zone exhibited the highest fine root production value (Fig 3), which can be attributed to its higher species density and lower sized trees compared to the mesohaline zone. Similar findings were also reported by Adame et al. (2017) that denser forest and small sized trees can produce higher root biomass compared to lesser density and higher sized trees. The FRP is greatly influenced and regulated by forest structure. When the density of trees increases, competition for limited resources becomes more intense, leading to higher FRP (Lopez et al. 1998; Ahmed et al. 2021). Previous research by Feller et al. (2003) and Mckee et al. (2007) observed that fine roots in mangrove ecosystems exhibit sensitivity to variations in nutrient availability. Wahid et al. (2007) showed that the oligohaline zone has higher levels of freshwater flow and nutrients than other salinity zones. Besides, Khan and Amin (2019) also reported that the soils in the oligohaline zone of the SMF contain a considerable amount of water-soluble and exchangeable nutrients. Therefore, it is reasonable that this nutrient-rich soil contributes to the higher production of fine roots in the oligohaline zone compared to the mesohaline zone. According to Chen et al. (2010), fine roots are highly susceptible to salt stress compared to the above-ground plant parts, leading to a significant decline in nutrient absorption. Due to the significant concentrations of salt, plants to evacuate water and obstructed their capacity to absorb it, which hindered plant development, particularly reducing the growth rate of fine roots (Imada et al., 2013). Therefore, the development of fine root formation would be lower.

Our current investigation unveiled that the FRP range (2.1-2.4 Mg ha^{-1} yr^{-1}) in the SMF exceeded the range of (1.0-1.5 Mg ha^{-1} yr^{-1}) reported in a subtropical mangrove located in the Florida Coastal Everglades, USA (Castaneda-Moya et al. 2011). The present FRP range was lower compared to the values (3.40-4.07 Mg ha^{-1} yr^{-1}) reported in the *Avicennia, Rhizophora*, and the *Xylocarpus* zones of a secondary mangrove forest in eastern Thailand (Poungparn et al. 2016). The variation in FRP could be attributed to climate disparities and species composition (Meinen et al., 2009), and age differences in forest stands (Idol et al., 2000) (Table 5). The FRP may also be affected due to the short life span of fine roots (Li et al. 2013). Several factors influence the lifespan of fine roots, such as their diameter, tissue density, nitrogen concentration, mycorrhizal fungal colonization, and the accumulation of secondary phenolic substances (Eissenstat et al. 2000). Finally, the laborious fine root sorting task and sample errors might also contribute to the disparity between the current study and prior studies on FRP. It is important to note that the selected study plots in this research do not encompass the whole of the Sundarbans. Our research examined two salinity zones out of three, so it would be worthwhile for future studies to explore the influence of high salinity on fine root production. This could provide valuable insights into the potential effects of salinity on the formation of fine roots.

Table 5. Variation in the estimation of fine root production across different forest communities across the world.

Forest Type	Study area and country	Root production ($gm^{-2}d^{-1}$)	Method of calculation	References
Sundarbans mangrove forest	Bangladesh	0.62	Simplified decision matrix	This study
***Quercus serrata* plantation**	Tsukuba, Japan	0.60	Combined method (Ingrowth core + Root Scanner)	Van Do et al. (2016)
A boreal mixed-wood forest	Ontario, Canada	1.89	Simplified decision matrix	Yuan and Chen (2013)
Upland temperate deciduous forests	Southern Indiana, USA	7.3 (4-year-old stand) 8.0 (10-year-old stand) 6.1 (29-year-old stand)	Measured as sum of the mass of fine roots extracted from the ingrowth core	Idol et al. (2000)
Temperate broad-leaved forest	Thuringia, Germany	1.38	Soil core, "minimum–maximum method'	Meinen et al. (2009)
80-year-old plantation of *Chamaecypari obtusa*	Ohtsu, Japan	3.24	Soil core, continuous inflow method	Osawa and Aizawa (2012)
A sub-tropical forest	Sanming, Fujia, China	1.18	Soil cores, compartment-flow method	Yang et al. (2007)
Primary tropical old-growth rainforest	Amazonia forests	2.3 (Closed canopy) 2.1 (Caxiuana˜, Brazil) 1.9 (Tambopata, Peru)	Measured as sum of the mass of fine roots extracted from the ingrowth core	Araga˜o et al. (2009)

Conclusion

The outcomes of this present study showed that the fine root biomass (FRB) and fine root production (FRP) of mangrove species is primarily manipulated by salinity, species composition, and tree size classes. In addition, the oligohaline zone played a significant role in promoting overall root production by providing an abundant supply of freshwater and nutrient-rich soil, leading to enhanced growth of roots. The classification of fine roots based on diameter classes enabled a detailed perception of the production process of fine roots. However, the sampling period and computation techniques influenced how fine root production was estimated. Fine root production can play a critical role in the forest's below-ground carbon sink. This highlights the crucial role of fine roots in nutrient uptake and the sequestration of atmospheric carbon, emphasizing the need to consider their contribution in future studies. We conclude that future research in the Sundarbans mangrove forest should consider the differentiation of fine roots in carbon dynamics among several mangrove species based on seasonal fluctuation, soil temperature, and inundation time, particularly in the three distinct salinity zones.

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Conflict of Interests
The authors declare no conflict of interest.

References

Adame, M. F., Teutli, C., Santini, N. S., Caamal, J. P., Zaldívar-Jiménez, A., Hernández, R., & Herrera-Silveira, J. A. (2014). Root biomass and production of mangroves surrounding a karstic oligotrophic coastal lagoon. *Wetlands*, *34*, 479-488.

Adame, M. F., Cherian, S., Reef, R., & Stewart-Koster, B. (2017). Mangrove root biomass and the uncertainty of belowground carbon estimations. *Forest Ecology and Management*, *403*, 52-60.

Ahmed, A., Aziz, A., Khan, A. N. A., Islam, M. N., Iqubal, K. F., Nazma, M., & Islam, M. S. (2011). Tree diversity as affected by salinity in the Sundarbans mangrove forests, Bangladesh. *Bangladesh Journal of Botany*, *40*(2), 197-202.

Ahmed, S., Kamruzzaman, M., Azad, M. S., & Khan, M. N. I. (2021). Fine root biomass and its contribution to the mangrove communities in three saline zones of Sundarbans, *Bangladesh. Rhizosphere*, *17*, 100294.

Ahmed, S., Sarker, S. K., Friess, D. A., Kamruzzaman, M., Jacobs, M., Sillanpää, M., & Pretzsch, H. (2023). Mangrove tree growth is size-dependent across a large-scale salinity gradient. *Forest Ecology and Management*, *537*, 120954.

Alongi, D. M. (2011). Carbon payments for mangrove conservation: ecosystem constraints and uncertainties of sequestration potential. *Environmental science & policy*, *14*(4), 462-470.

Aziz, A., & Paul, A. (2015). Bangladesh Sundarbans: present status of the environment and biota. *Diversity, 7*(3), 242-269.

Castañeda-Moya, E., Twilley, R. R., Rivera-Monroy, V. H., Marx, B. D., Coronado-Molina, C., & Ewe, S. M. (2011). Patterns of root dynamics in mangrove forests along environmental gradients in the Florida Coastal Everglades, USA. *Ecosystems*, *14*(7), 1178-1195.

Chaffey, D.R., Miller, F.R., & Sandom, J.H. (1985). A forest inventory of the Sundarban, Bangladesh. Project Report 140, *Land Resources Development Centre, Surrey, England*. p 196.

Chave, J., D. A. Coomes, S. Jansen, s. L. Lewis, n. G. Swenson, and a. E. Zanne. (2009). towards a worldwide wood economics spectrum. *Ecol. Let. 12*, 351−366.

Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B., & Vieilledent, G. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global change biology*, *20*(10), 3177-3190.

Chen, W.P., Hou, Z.N., Wu, L.H., Liang, Y.C., Wei, C.Z. (2010). We are evaluating salinity distribution in soil irrigated with saline water in arid regions of northwest China. *Agric Water Manag 97*:2001–2008.

Christensen, B. (1978). Biomass and primary production of *Rhizophora apiculata* Bl. in a mangrove in southern Thailand. *Aquatic Botany*, *4*, 43-52.

Cintron, G., & Novelli, Y. S. (1984). Methods for studying mangrove structure. In Mangrove ecosystem: research methods (pp. 91-113). UNESCO.

Eissenstat, D. M., Wells, C. E., Yanai, R. D., & Whitbeck, J. L. (2000). Building roots in a changing environment: implications for root longevity. *The New Phytologist*, *147*(1), 33-42.

Fairley, R. I. (1985). Methods of calculating fine root production in forests. *Ecological Interactions in the Soil*, 37-41.

Feller, I. C., Whigham, D. F., McKee, K. L., & Lovelock, C. E. (2003). Nitrogen limitation of growth and nutrient dynamics in a disturbed mangrove forest, Indian River Lagoon, Florida. *Oecologia*, *134*(3), 405-414.

Finér, L., Ohashi, M., Noguchi, K., & Hirano, Y. (2011). Factors causing variation in fine root biomass in forest ecosystems. *Forest Ecology and Management*, *261*(2), 265-277.

Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J. L., & Cadamuro, L. (1998). Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. *Oecologia*, *115*(1-2), 39-53.

Gifford, R. M. (2000). Carbon contents of above-ground tissues of forest and woodland trees. National Carbon Accounting System Technical Report No. 22. Australian Greenhouse Office, Canberra

Heimann, M., & Reichstein, M. (2008). Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature*, *451*(7176), 289-292.

Heimann, M., Keeling, C. D., & Tucker, C. J. (1989). A three-dimensional model of atmospheric CO_2 transport based on observed winds: 3. Seasonal cycle and synoptic time scale variations. *Aspects of climate variability in the Pacific and the Western Americas*, *55*, 277-303.

Hendrick, R. L., & Pregitzer, K. S. (1993). The dynamics of fine root length, biomass, and nitrogen content in two northern hardwood ecosystems. *Canadian journal of forest research*, *23*(12), 2507-2520.

Hendricks, J. J., Hendrick, R. L., Wilson, C. A., Mitchell, R. J., Pecot, S. D., & Guo, D. (2006). Assessing the patterns and controls of fine root dynamics: an empirical test and methodological review. *Journal of Ecology*, 40-57. How mangrove forests adjust to rising sea level. New Phytologist.

Helmisaari, H. S., Makkonen, K., Kellomäki, S., Valtonen, E., & Mälkönen, E. (2002). Below-and above-ground biomass, production and nitrogen use in Scots pine stands in eastern Finland. *Forest ecology and management*, *165*(1-3), 317-326.

Hossain, M., Siddique, M. R. H., Saha, S., & Abdullah, S. R. (2015). Allometric models for biomass, nutrients and carbon stock in Excoecaria agallocha of the Sundarbans, Bangladesh. *Wetlands ecology and management*, *23*, 765-774.

Idol, T. W., Pope, P. E., & Ponder Jr, F. (2000). Fine root dynamics across a chronosequence of upland temperate deciduous forests. *Forest Ecology and Management*, *127*(1-3), 153-167.

Imada, S., Taniguchi, T., Acharya, K., & Yamanaka, N. (2013). Vertical distribution of fine roots of *Tamarix ramosissima* in an arid region of southern Nevada. *Journal of arid environments*, *92*, 46-52.

Jackson, R., Mooney, H. A., & Schulze, E. D. (1997). A global budget for fine root biomass, surface area, and nutrient contents. *Proceedings of the National Academy of Sciences*, *94(*14), 7362-7366.

Kamruzzaman, M., Ahmed, S., Paul, S., Rahman, M. M., & Osawa, A. (2018). Stand structure and carbon storage in the oligohaline zone of the Sundarbans mangrove forest, Bangladesh. *Forest Science and Technology*, *14*(1), 23-28.

Kauffman, J. B., Heider, C., Cole, T. G., Dwire, K. A., & Donato, D. C. (2011). Ecosystem carbon stocks of Micronesian mangrove forests. *Wetlands, 31*(2), 343-352.

Khan, M. N. I., Suwa, R., & Hagihara, A. (2007). Carbon and nitrogen pools in a mangrove stand of *Kandelia obovata* (S., L.) Yong: vertical distribution in the soil–vegetation system. *Wetlands Ecology and Management, 15*, 141-153.

Khan, M. Z., & Amin, M. S. (2019). Macro nutrient status of Sundarbans Forest soils in Southern region of Bangladesh. *Bangladesh Journal of Scientific and Industrial Research*, *54*(1), 67-72.

Klimešová, J., Latzel, V., de Bello, F., & van Groenendael, J. M. (2008). Plant functional traits in studies of vegetation changes in response to grazing and mowing: towards a use of more specific traits. *Preslia*, *80*(3), 245-253.

Komiyama, A., Poungparn, S., & Kato, S. (2005). Common allometric equations for estimating the tree weight of mangroves. *Journal of tropical ecology*, *21*(4), 471-477.

Krauss KW, McKee KL, Lovelock CE, Cahoon DR, Saintilan N, Reef R, Chen L (2013). How mangrove forests adjust to rising sea level. *New Phytologist.*

Kusmana, C., & SABIHAM, S. (1992). An estimation of above-ground tree biomass of a mangrove forest in East Sumatra, Indonesia. *Tropics*, *1*(4), 243-257.

Li, X., Zhu, J., Lange, H., & Han, S. (2013). A modified ingrowth core method for measuring fine root production, mortality and decomposition in forests. *Tree Physiology*, *33*(1), 18-25.

Liu, H., Ren, H., Hui, D., Wang, W., Liao, B., & Cao, Q. (2014). Carbon stocks and potential carbon storage in the mangrove forests of China. *Journal of Environmental Management*, *133*, 86-93.

López, B., Sabaté, S., & Gracia, C. (1998). Fine roots dynamics in a Mediterranean forest: effects of drought and stem density. *Tree physiology*, *18*(8-9), 601-606.

López, B., Sabaté, S., & Gracia, C. A. (2001). Fine-root longevity of Quercus ilex. *New Phytologist*, *151*(2), 437-441.

McKee, K. L., Cahoon, D. R., & Feller, I. C. (2007). Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography*, *16*(5), 545-556.

Meinen, C., Hertel, D., & Leuschner, C. (2009). Root growth and recovery in temperate broad-leaved forest stands differing in tree species diversity. *Ecosystems*, *12*(7), 1103-1116.

Mitra, A., Sengupta, K., & Banerjee, K. (2011). Standing biomass and carbon storage of above-ground structures in dominant mangrove trees in the Sundarbans. *Forest Ecology and Management*, *261*(7), 1325-1335.

Naidoo, G. (2009). Differential effects of nitrogen and phosphorus enrichment on growth of dwarf Avicennia marina mangroves. *Aquatic Botany*, *90*(2), 184-190.

Neill, C. (1992). Comparison of soil coring and ingrowth methods for measuring belowground production. *Ecology, 73*(5), 1918-1921.

Nagarajan, B., Pandiarajan, C., Krishnamoorthy, M., & Sophia, P. (2008). Reproductive fitness and success in mangroves: implication on conservation. *In Proceedings of Taal The 12th World Lake Conference* (pp. 29-33).

Osawa, A., & Aizawa, R. (2012). A new approach to estimate fine root production, mortality, and decomposition using litter bag experiments and soil core techniques. *Plant and Soil, 355*(1), 167-181.

Ostonen, I., Lõhmus, K., & Pajuste, K. (2005). Fine root biomass, production and its proportion of NPP in a fertile middle-aged Norway spruce forest: comparison of soil core and ingrowth core methods. *Forest Ecology and Management*, *212*(1-3), 264-277.

Padalia, H., Chauhan, N., Porwal, M. C., & Roy, P. S. (2004). Phytosociological observations on tree species diversity of Andaman Islands, India. *Current Science*, 799-806.

Perera, K. A. R. S., Amarasinghe, M. D., & Somaratna, S. (2013). Vegetation structure and species distribution of mangroves along a soil salinity gradient in a micro-tidal estuary on the north-western coast of Sri Lanka. *American Journal of Marine Science*, *1(*1), 7-15.

Poungparn, S., Komiyama, A., Sangteian, T., Maknual, C., Patanaponpaiboon, P., & Suchewaboripont, V. (2012). High primary productivity under submerged soil raises the net ecosystem productivity of a secondary mangrove forest in eastern Thailand. *Journal of Tropical Ecology*, *28*(3), 303-306.

Poungparn, S., Charoenphonphakdi, T., Sangtiean, T., & Patanaponpaiboon, P. (2016). Fine root production in three zones of secondary mangrove forest in eastern Thailand. *Trees*, *30*(2), 467-474.

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rahman, M. R., & Asaduzzaman, M. (2010). Ecology of sundarban, bangladesh. *Journal of Science Foundation*, *8*(1-2), 35-47.

Ray, R., Ganguly, D., Chowdhury, C., Dey, M., Das, S., Dutta, M. K. ... & Jana, T. K. (2011). Carbon sequestration and annual increase of carbon stock in a mangrove forest. *Atmospheric Environment*, *45*(28), 5016-5024.

Roy, S. D., & Krishnan, P. (2005). Mangrove stands of Andamans vis-à-vis tsunami. *Current Science*, *89(*11), 1800-1804.

Ross, M. S., Ruiz, P. L., Telesnicki, G. J., & Meeder, J. F. (2001). Estimating above-ground biomass and production in mangrove communities of Biscayne National Park, Florida (USA). *Wetlands Ecology and Management*, *9*(1), 27-37.

Siddique, M. R. H., Zuidema, P. A., Sass-Klaassen, U., & Chowdhury, M. Q. (2021). Ring width and vessel features of the mangrove *Excoecaria agallocha* L. depend on salinity in the Sundarbans, Bangladesh. *Dendrochronologia, 68*, 125857.

Sitoe, A., Mandlate, L., & Guedes, B. (2014). Biomass and carbon stocks of Sofala bay mangrove forests. *Forests*, *5*(8), 1967-1981.

Suzuki, E., & Tagawa, H. (1983). Biomass of a mangrove forest and a sedge marsh on Ishigaki Island, south Japan. *Japanese Journal of Ecology*, *33*(2), 231-234.

Tomlinson, P.B. (1986). The Botany of Mangroves. Cambridge University Press, Cambridge, U.K. 413 pp.

Trumbore, S. E., & Gaudinski, J. B. (2003). The secret lives of roots. *Science, 302(*5649), 1344-1345.

Uddin, M. M., Hossain, M. M., Aziz, A. A., & Lovelock, C. E. (2022). Ecological development of mangrove plantations in the Bangladesh Delta. *Forest Ecology and Management*, *517*, 120269.

Van Do, T., Sato, T., & Kozan, O. (2016). A new approach for estimating fine root production in forests: a combination of ingrowth core and scanner. *Trees*, *30*, 545-554.

Wahid, S. M., Babel, M. S., & Bhuiyan, A. R. (2007). Hydrologic monitoring and analysis in the Sundarbans mangrove ecosystem, Bangladesh. *Journal of Hydrology*, *332(*3-4), 381-395.

Wang, G., Guan, D., Peart, M. R., Chen, Y., & Peng, Y. (2013). Ecosystem carbon stocks of mangrove forest in Yingluo Bay, Guangdong Province of South China. *Forest Ecology and Management*, *310*, 539-546. Washington, pp 225–249.

Westoby, M., Falster, D. S., Moles, A. T., Vesk, P. A., & Wright, I. J. (2002). Plant ecological strategies: some leading dimensions of variation between species. *Annual review of ecology and systematics*, *33*(1), 125-159.

Xiao, C. W., Sang, W. G., & Wang, R. Z. (2008). Fine root dynamics and turnover rate in an Asia white birch forest of Donglingshan Mountain, China. *Forest Ecology and Management*, *255*(3-4), 765-773.

Yang, L., Wu, S., & Zhang, L. (2010). Fine root biomass dynamics and carbon storage along a successional gradient in Changbai Mountains, China. *Forestry*, *83*(4), 379-387.