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Stand structure and carbon storage of a young mangrove plantation forest in coastal area of Bangladesh: The promise of a natural solution

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A R T I C L E I N F O

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A B S T R A C T

Globally, with the growing importance of mangroves for providing ecosystem services and mitigating climate change, it is still uncertain whether planted mangroves can be the counterpart of natural mangroves, and thus the role of planted mangroves is still less understood. Therefore, this study aimed to assess the stand structure and carbon storage of a young mangrove plantation in Satkhira District, Bangladesh and to compare it with the natural mangrove forest (i.e., Sundarbans) to understand the potential of this young mangrove plantation as a nature-based solution to climate change. In addition, to better understand the spatial dynamics of afforested mangrove forests, we investigated and compared both above and below-ground carbon stocks between the landward and riverward sites. We collected both above (height and diameter at breast height, DBH) and belowground (i.e., coarse and fine root) data from 16 plots with a total area of 1600 m^2 in two paired transects, eight plots each in landward and riverward sites. Aboveground carbon stocks were estimated using the species-specific allometric models from the biophysical tree parameters (i.e., height and DBH). Besides, belowground root ($\geq$ 20 mm) carbon was measured by direct weighting after collecting soil samples through coring. Stand structural attributes (i.e., density, basal area, and DBH) showed a significant difference between the two sites, whereas *Sonneratia apetala* was found as the dominant species (IV = 188.7~207.1) in both forest sites. The mean carbon stock of this plantation was 49.1 Mg C ha^{-1}, while the mean aboveground carbon (AGC) was 37.3 Mg C ha^{-1}. The landward site contributed significantly more AGC (40.1 Mg C ha^{-1}) than the riverward (34.4 Mg C ha^{-1}) site ($p<0.05$). Besides, the mean belowground roots carbon (BGRC) of this plantation was 11.8 ± 1.4 Mg C ha^{-1}, where the riverward site contributed significantly more root carbon (14.3 Mg C ha^{-1}) than the landward site (9.4 Mg C ha^{-1}) ($p<0.05$). Tree density and basal area showed a significant positive relationship with BGRC. Although only two species were planted, after 15 years, we observed the total number of species reached nine. The carbon stock, progressive species richness in this plantation reflects the significance of young mangrove plantations in sequestering carbon to mitigate climate change and biodiversity conservation as nature-based solutions which may be useful for future coastal afforestation and restoration programs.

1. Introduction

Mangrove forests, located in the tropics and subtropics, are highly productive and unique ecosystems with powerful carbon sinks [1–3]. Mangroves can efficiently sink three to five times more carbon than terrestrial forests, and therefore, these forests are considered carbon-dense ecosystems [4,5]. However, over the last centuries, mangrove forests have been severely depleted all over the world [6,7]. Therefore, mangrove restoration and conservation are now considered as nature-based solutions for reinforcing the adaptive capability of vulnerable mangrove regions to confront global warming and sea-level rise through capturing atmospheric carbon [2,8,9]. Thus, worldwide, many countries have started plantations with mangroves, predominantly with monogenetic species, to restore their degraded mangrove

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areas or afforest newly accredited land, including Bangladesh [10]. In turn, these mangrove plantations, provide some short-term gains in forest area; however, long-term functional capabilities and ecosystem services are underappreciated in the literature [11,12]. Coastal mangrove plantations provide numerous ecosystem services by providing timber, fuelwood, managing the watersheds, protecting from natural calamities such as storms and tidal surges, stabilizing the accreted shoreline or land, conserving biodiversity, adding nutrients to soil, reducing soil erosion with diverse rooting systems, and mitigating climate change by sequestering carbon as biomass [13–16]. Since 1960, the government of Bangladesh has afforested about 280 km^2 areas under mangrove plantations aiming at protecting from natural calamities, stabilizing the land, and providing support to the local community [13,14,17,18]. Despite the massive plantations in the coastal areas and riverbanks in Bangladesh, we are still unaware of the potential of young mangrove plantations. To illustrate, whether the forest structure, biodiversity, and biomass or carbon (above and below) stock in young mangrove plantations in newly accreted land can compensate for the natural mangroves in the same region, e.g., the Sundarbans in Bangladesh. It is believed that the carbon sequestration capability and overall ecosystem carbon stocks are increased in mangrove plantations with age, which is analogous to natural mangroves [19,20].

The ecosystem carbon stock of any forest is the combination of carbon stored in tree shoots, roots, downed wood, and sediment, where sediment is the most significant contributor of carbon in mangroves [5]. Next to sediment, the aboveground tree and belowground live roots are the major contributors to the remaining carbon density of mangroves, which can vary with stand types, nutrient availability, salinity, and flooding [3,21-23]. However, very few studies estimated root biomass due to difficulty in measurement and labor-intensive [24]. Therefore, most studies relied on allometric models, which systematically convert the aboveground estimates to belowground components [25]. Globally, a handful of studies have inventoried and estimated mangrove biomass and carbon storage, aiming to enhance the understanding of ecosystem functions and services [16,26-30]. Inventory data from restored and afforested mangroves reveals that they can regain their previous condition or alike within decades, including structure, composition, and carbon storage [31–35]. These remarkable gain in carbon, both above and belowground, pave the way for climate change mitigation; but it depends on age, species, site condition, landscape position, and management regime [32,36,37]. These disparities in carbon gain call for ongoing monitoring of structure and carbon stock, as well as implementation of appropriate adaptive management strategies for any restoration or afforestation projects [32,38]. Thus, information on stand structure, composition, and carbon stock estimation is crucial for a better understanding of ecosystem functions and traits [39].

In addition, understanding the spatial pattern (e.g., landward vs. riverward) of stand structure, composition, and carbon stock is critical to getting information on ecosystem functions and services [40,41]. Furthermore, due to variation in physical and chemical properties of soil, tidal inundation, and anthropogenic influence, growth and productivity vary spatially between landward and riverward or seaward [41–43]. Therefore, the spatial pattern of the structure, composition, and carbon storage is critical for understanding any afforested projects' growth dynamics and being a successful conservation project. Considering all these, we aimed (1) to estimate the stand structure, composition, and live tree carbon storage of a young mangrove plantation (i.e., Ruposhi Mangrove Plantation (RMP) in Bangladesh), (2) to compare the structure, composition, and carbon storage of a young mangrove plantation between riverward and landward sites, and (3) to check the relationships and variations of belowground root carbon stock with stand structure and sites. We hypothesized that (1) the differences in soil physical and chemical properties along the riverward would result in different species composition, structure, and carbon storage of the live trees from the landward site. We also envisaged that (2) belowground root carbon is significantly influenced by stand variables such as stand density, basal area etc. In addition, we compared the results with those of natural mangrove forests i.e., the Sundarbans, to understand the young mangrove potential and draw broader attention. Therefore, this information may be useful for future coastal plantation and restoration programs.

2. Materials and methods

2.1. Study site

Since the 1960s, Bangladesh has been known for coastal afforestation to protect the lives and properties of coastal communities from tropical cyclones and tidal surges [18,44]. Presently, Bangladesh has about 200,000 ha of coastal mangrove forests under the afforestation program [45]. The choice of mangrove species for planting, using simple and easy techniques of nursery raising and plantation establishment, the higher rate of seedling survivability, and site suitability of the newly accreted lands may trigger the successful and massive monoculture of *Avicennina officinalis* and *Sonneratia apetala* in Bangladesh, which have turned into the world's largest planted mangroves.

The Bangladesh Forest Department (BFD) established a mangrove plantation in the Ruposhi mangrove plantation (RMP) located in Debhata subdistrict in Satkhira District, which is located at 22° 56′N and 88° 94E on the bank of the Isamoti River, near the Bangladesh-Indian borderline (Fig. 1A).

The BFD started plantation in RMP in 2003-05 with *A. officinalis* and *S. apetala* species to protect the locality from strong winds and cyclonic events and protect the riverbanks. The landward side is surrounded by shrimp-based aquaculture with saline water. The land is relatively flat, and the surface elevation is between -0.3 and 2.02 m from the mean sea level. In 2018, the mean annual rainfall and temperature were 1655 mm and 26.2°C, respectively [46]. The area is regularly inundated by saline water from the river Isamoti.

2.2. Sampling design and data collection

We established a total of 16 (10 m × 10 m) systematic sampling plots in 2018 by following paired sampling on both the landward and riverward sides of the RMP, covering an area of around 1600 m^2 area (Fig. 1). Thus, the sampling design constitutes 8 plots in each riverward and landward and 50 m apart from each other. The average length of the forest from landward to riverward was 220 m. To avoid edge effects, we included all trees touching the edge of the sampling boundary. We identified and recorded all individuals within the plots. For the structural properties, we measured the diameter at 130 cm and the height of each tree species ($\geq$ 2cm at D_{130cm}) with a diameter tape and a Criterion RD 1000 Electronic Dendrometer (Laser Technology Incorporation, USA), respectively.

2.3. Forest structure and biodiversity index

We quantified the species composition, tree density (stem ha^{-1}), and basal area (m^2 ha^{-1}) of each sample plot. A structural index such as importance value (IV) was calculated by using the following formulas according to G mCintrón [47].

IV= relative (tree density + frequency + dominance).

2.4. Estimation of carbon stock

2.4.1. Aboveground carbon stock (AGC)

The study area is dominated by mainly two pioneer species (*S. apetala* and *A. officinalis*). Species-specific allometric models provide a more accurate estimate of biomass or carbon in mangroves [48]. Therefore, we used a site-specific allometric equation for total aboveground biomass (TAGB) of *S. apetala* in the coastal mangrove forest by [49].

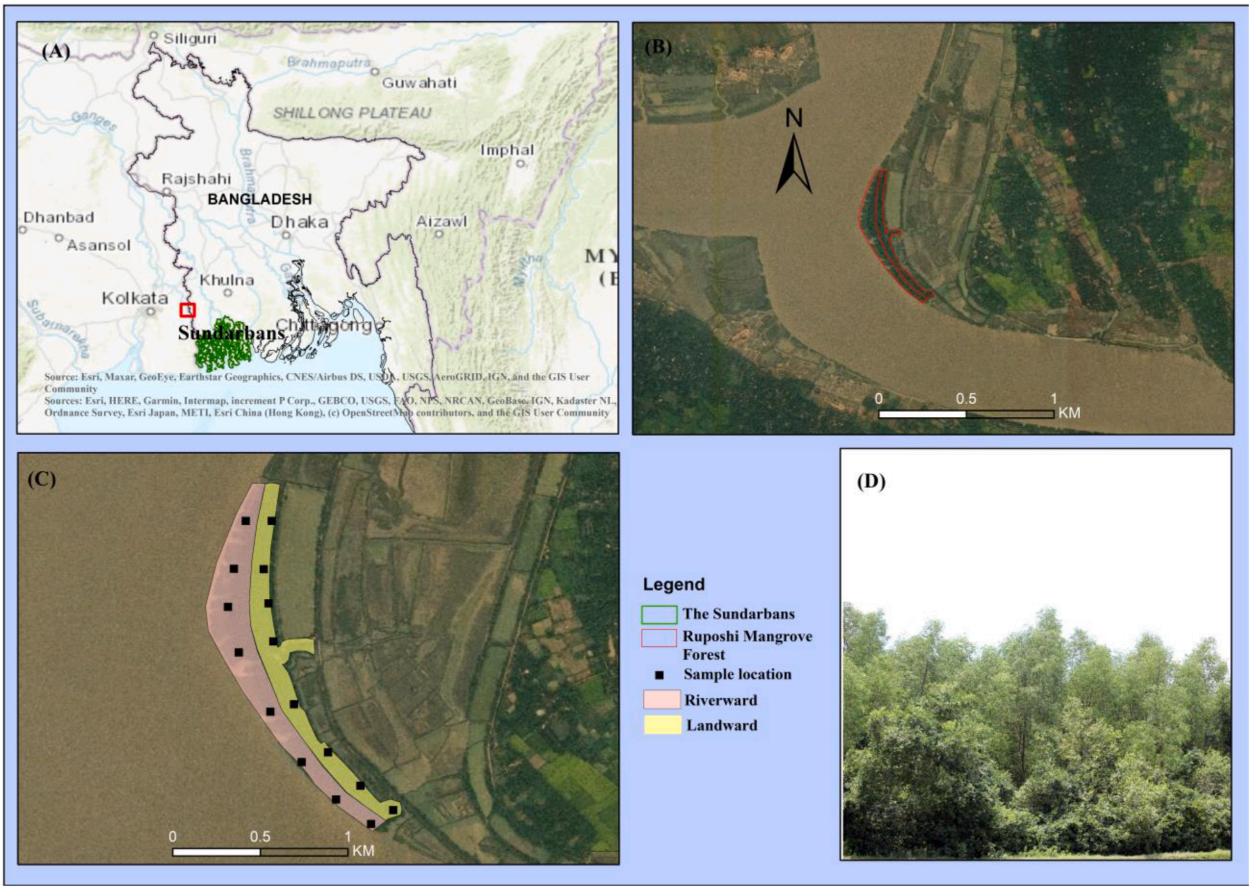

Fig. 1. Study map showing (A) location of Ruposhi Mangrove Plantation (RMP) in Bangladesh, (B) study site, (C) design of sample plots and pair lines in the study area, with pink shading indicating riverward and yellow shading indicating landward, (D) the RMP. Using QGIS version 3.16, Hannover used to formulate A-C and D was captured during data collection. The background satellite images were collected from Google Maps inside the QGIS environment.

$$\mathrm{Ln}\ (\mathrm{TAGB}) = -1.7608 + 2.0077*\mathrm{Ln}\ (\mathrm{D}) + 0.2981*\mathrm{Ln}\ (\mathrm{H})$$

Where D and H denote diameter at 130 cm and height, respectively, after getting the total biomass from the equation, total carbon was calculated by multiplying 0.5 [50] and later expressed as Mg C ha^{-1}.

2.4.2. Belowground root carbon stock (BGRC)

To estimate belowground root carbon stock, four sediment cores, each at 40 cm soil depth, were collected randomly from each sample plot with a stainless steel sediment corer according to Addo-Danso et al. [51]. The diameter of the sediment corer was 10 cm, and the length was 50 cm. Soil samples of 40 cm were kept for analysis to avoid compaction in the bottom 10 cm of the corer. Again, this study highlighted and used top 40 cm because the live roots of mangroves are usually stored within 30-35 cm of soil depth [52,53]. After collection, we divided the soil depth into four sections of equal 10 cm intervals (0-10 cm, 11-20 cm, 21-30 cm, and 31-40 cm). Soil samples were then marked, stored in polythene bags, and brought back to the laboratory of the Forestry and Wood Technology Discipline, Khulna University, Bangladesh for further analysis.

The soil particles were washed away from the roots with water using a steel sieve with a minimal mesh size of 0.25 mm in the laboratory. After washing, floating live roots were separated from the dead roots, accumulated at the bottom, according to Castañeda-Moya et al. [53]. The live roots were then classified as fine roots (≤ 2 mm), medium roots (2-5 mm), and coarse roots (5-20 mm) using three different mesh sizes i. e., 2 mm, 5 mm, and 20 mm, respectively. The separated roots were weighted before and after being oven-dried at 60°C until they reached a constant weight. The final root biomass was calculated and subsequently converted to carbon according to Gifford [50] and later expressed as Mg C ha^{-1}.

2.5. Statistical analysis

Our collected tree structural and carbon stock data from both riverward and landward in Ruposhi Mangrove Plantation (RMP) were used to test the hypotheses. A one-sample t-test was used, followed by Fisher's Least Significant Difference (LSD) test to address the first hypothesis i.e., differences in structural parameters and carbon storage (i. e., above and root) between the RMP riverward and landward sites. A two-way ANOVA (analysis of variance) was performed to determine significant differences in root biomass among study sites and soil depths, where sites and depth are considered fixed factors. The assumptions for the normality test and homogeneity of variance were met before the actual t-test and ANOVA. When ANOVA showed a significant difference, pairwise comparisons were made by using Bonferroni post hoc tests. To check the relationship among belowground root carbon stock and structural attributes i.e., second hypothesis, we performed regression analysis. In all tests, we used a 95% level of significance. All the statistical analyses and the figures were drawn using R version 3.1.5 [54].

3. Results

3.1. Stand structure and species composition

This study recorded a total of nine species under six families in both sites (Table 1).

Acanthaceae was the most dominant family, which included

Table 1
Overview of tree species richness and regeneration (i.e., seedling availability) status of the RMP after 15 years. 1 and 2 indicate the riverward and landward sites, respectively.

Observed mature tree species				Observed seedling regeneration		
Sl. No	Local name	Species	Family	Sl No	Species	Family
1	Kala Baen[12]	*Avicennia officinalis* L.	Acanthaceae	1	*Sonneratia apetala* Buch -Ham. [12]	Lythraceae
2	Keora[12]	*Sonneratia apetala* Buch -Ham.	Lythraceae	2	*Avicennia officinalis* L. [12]	Acanthaceae
3	Moricha Baen[2]	*Avicennia marina* (Forssk.) Vierh	Acanthaceae	3	*Sonneratia caseolaris* (L.) Engl. [1*2]	Lythraceae
4	Kakra[1]	*Bruguiera sexangula* (Lour.) Poir.	Rhizophoraceae	4	*Bruguiera sexangula* (Lour.) Poir. [2]	Rhizophoraceae
5	Vat Kathi[1]	*Kandelia candel*	Rhizophoraceae	5	*Nypa fruticans* Wurmb[1]	Arecaceae
6	Soila/Ora[12]	*Sonneratia caseolaris* (L.) Engl.	Lythraceae	6	*Kandelia candel*[1]	Rhizophoraceae
7	Lata Sundri[2]	*Brownlowia tersa* (L.) Kosterm.	Malvaceae			
8	Golpata[1]	*Nypa fruticans* Wurmb	Arecaceae			
9	Hargoza[12]	*Acanthus ilicifolius* L	Acanthaceae			

Avicennia officinalis, A. marina, and *Acanthus ilicifolius.* After 15 years of plantation in the RMP forest, the species richness has increased from 3 to 9. It includes some true mangrove species such as *Knadelia Kandel, Bruguiera Sexangula, Nypa fruticans*, and *Acanthus ilicifolius* (Table 1). The stand was dominated by mainly small-sized trees, with a diameter range of 2 to 10 cm. Diameter class distribution showed that the riverward site represents a lower frequency of trees exceeding 10 cm in diameter. In contrast, higher frequencies of diameter or large trees were found in the landward area (Fig. 2).

The structural composition of mangrove communities is shown in Tables 2 and 3.

The landward site had a 40% higher density than the riverward, and therefore, the complexity index is higher on the landward (Table 2). Irrespective of the site, the preponderance of *S. apetala* showed a higher importance value (IV) (Table 3).

Table 2
Stand structural parameters of mangrove communities in the RMP. The different letters indicate a significant difference between the sites (adjusted by Bonferroni post hoc test). Results are shown as mean ± standard error.

Site	Density (ha^{-1})	Basal area (m^2 ha^{-1})	Mean H (m)	Mean D_{130} (cm)
Riverward	1950 ± 451[a]	16.5 ± 0.9 [a]	8.4 ± 1.3 [a]	7.3 ± 0.9 [b]
Landward	1400 ± 209[b]	18.4 ± 1.3 [a]	9.1 ± 0.4 [a]	9.8 ± 1.3 [a]
Mean	1675 ± 330	17.5 ± 1.1	8.8 ± 1.4	8.8 ± 1.1

3.2. Above and belowground carbon stock

In both riverward and landward areas, *S. apetala* holds the highest basal area (Table 3). Therefore, because of its higher relative dominance, the contribution of *S. apetala* to the total biomass carbon was greater than that of *A. officinalis* (Table 4). Similarly, *A. officinalis* also

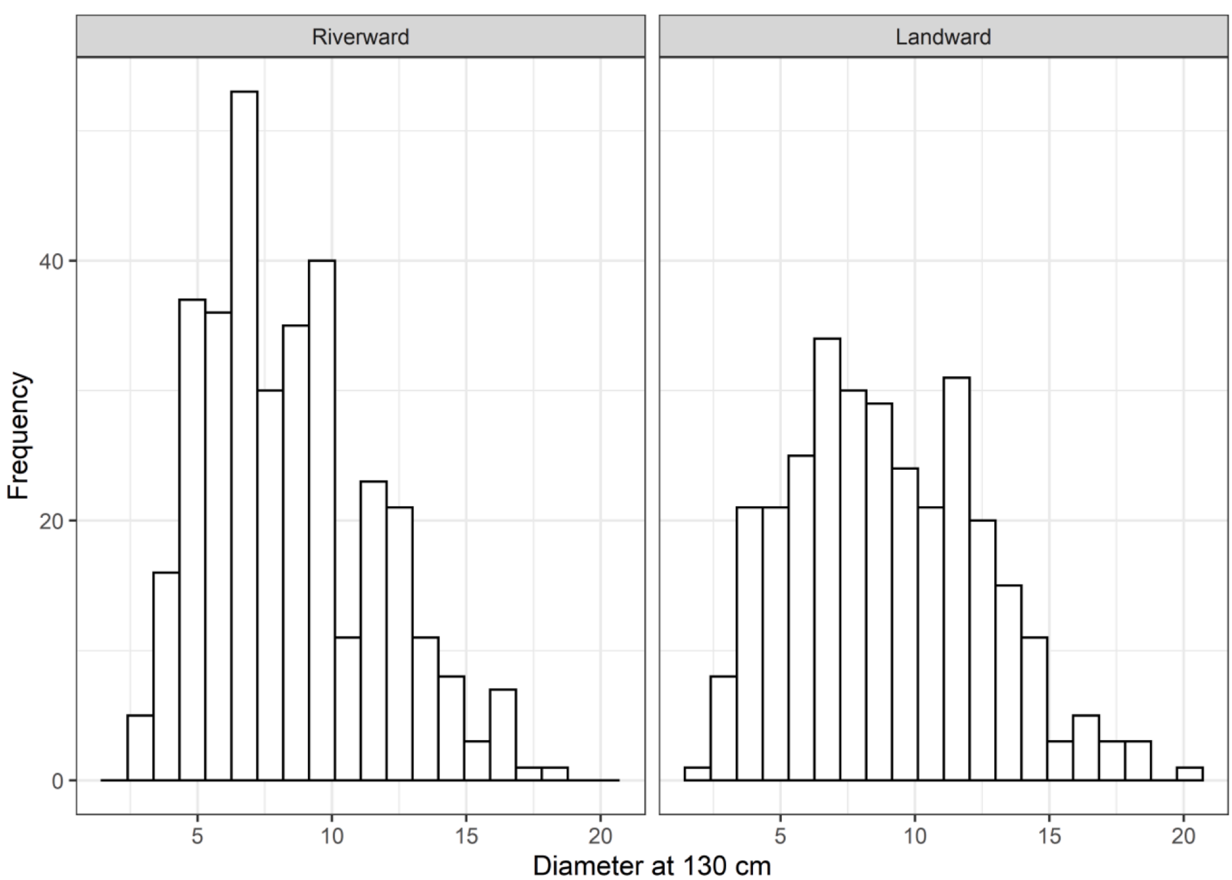

Fig. 2. Histogram of D_{130} cm (DBH) distribution in the RMP across riverward and landward sites.

Table 3
Structural composition of recorded major mangrove species in RMP.

Species	Tree density (n ha^{-1})	Basal area (m^2 ha^{-1})	Relative density (%)	Relative dominance (%)	Importance Value IV
Riverward					
S. apetala	1425	10.1	73.1	65.6	188.7
A. officinalis	525	6.4	26.9	34.4	111.3
Landward					
S. apetala	1100	14.4	78.6	78.6	207.1
A. officinalis	300	4.1	21.4	21.4	92.9

Table 4
Total above- and belowground live tree carbon in the RMP, Bangladesh. The different letters indicate a significant difference between the sites (adjusted by the Bonferroni post hoc test). Results are shown as the mean ± standard error.

Site	Aboveground carbon (Mg C ha^{-1})	Belowground root carbon (Mg C ha^{-1})	Total live tree carbon (Mg C ha^{-1})
Riverward	34.4 ± 2.5^{b}	14.3 ± 1.9^{a}	48.7 ± 4.4^{a}
Landward	40.1 ± 2.3^{a}	9.4 ± 0.9^{b}	49.5 ± 3.4^{a}
Mean	37.3 ± 2.4	11.8 ± 1.4	49.1 ± 3.9

contributed considerably to the total carbon stock of the studied plantation forest (Tables 3 and 4).

The mean aboveground carbon (AGC) and below-ground root carbon of the RMP were 37.3 and 11.58 Mg C ha^{-1}, respectively (Table 4). Statistical analysis (t-test) showed that the riverward site holds significantly ($p<0.05$) lower AGC stock than the landward site (Table 4). However, there was no significant ($p>0.05$) difference found in the case of the total live tree carbon stock, although carbon stock in the landward site was slightly higher than the riverward site (Table 4).

3.3. Belowground root carbon (BGRC) stock

The average BGRC stock in the RMP was 11.58 Mg C ha^{-1}. Two-way ANOVA indicates that total root carbon in the riverward site is significantly higher than the landward site ($F_{1, 200} = 14.6, p<0.001$) (Fig. 3A). The study also observed a significant difference between soil depth ($F_{3, 200} = 5.2, p<0.001$) and the interaction of study site and depth ($F_{3, 200} = 3.8, p<0.01$). Meantime, the coarse root class (5-20 mm) is significantly different between sites and depths ($F_{1, 200} = 13.9, p<0.001$; depth, $F_{3, 200} = 5.9, p <0.001$) which signifies a variable contribution to carbon stock than other root classes (Fig. 3B–D).

Moreover, the present study also showed that the top layer had higher root carbon than the bottom layer (Fig. 3A, B). In the riverward site, the contribution of the individual diameter class of roots revealed that 5-20 mm root contributed the most carbon than the other two diameter classes (Fig. 3B). Notably, medium and fine root (2-5 mm and ≤ 2 mm) diameter classes contributed almost a similar amount of root carbon throughout the sites and soil depth. (Fig. 3). The mean fine root (≤ 2 mm) carbon was 2.9 ± 0.6 Mg ha^{-1} in the studied mangrove plantation (Fig. 3D). However, no significant variation was observed between soil depth and sites in case of medium (2-5 mm) (site, $F_{1, 200} = 2.3, p>0.05$; depth, $F_{3, 203} = 1.0, p>0.05$) and fine root (≤2 mm) (site, $F_{1, 200} = 0.8, p>0.05$; depth, $F_{3, 200} = 2.5, p>0.05$) carbon stock (Fig. 3C and D).

The relationship between belowground root carbon (BGRC) and aboveground structural information such as tree density and basal area showed a significant positive relationship (Fig. 4). On the other hand, the mean height and aboveground carbon (AGC) showed an insignificant relationship with BGRC ($p>0.05$) (Fig. 4).

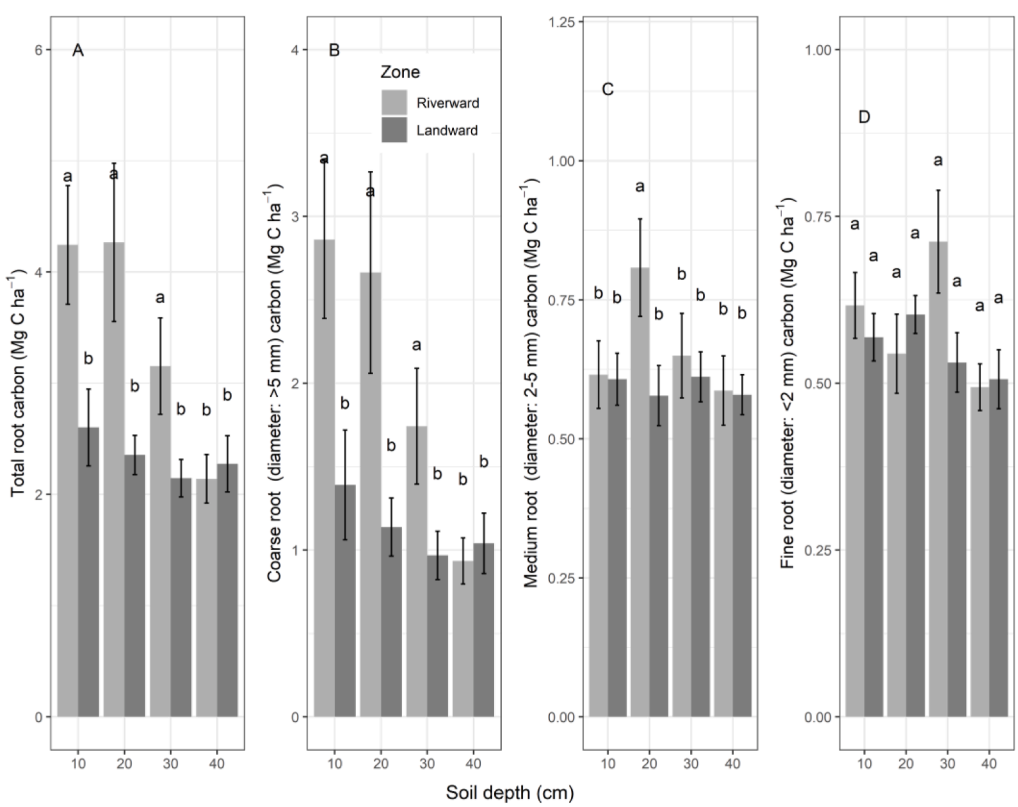

Fig. 3. Belowground root carbon stock (BGRC) across two sites at different soil depths. Error bars denote mean ± standard errors; a similar letter indicates no significant difference at $p <0.05$.

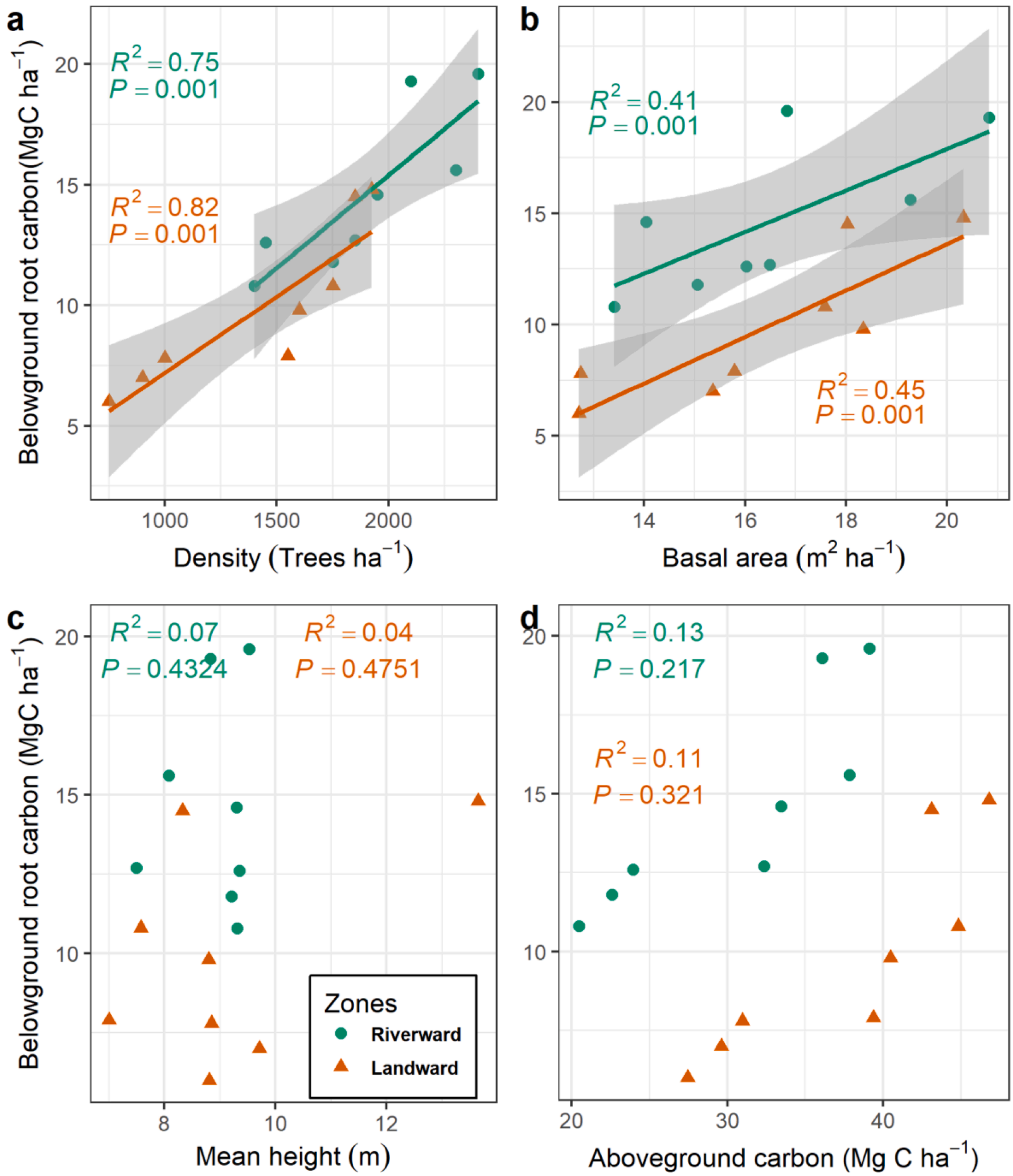

Fig. 4. Relationship between plot-wise root carbon stock and above ground structural parameters: a) Tree density, b) Basal area, c) Mean height, d) Aboveground carbon (AGC). The shaded area indicates a 95% confidence interval.

4. Discussions

4. 1 Stand structure and species composition

The entire Ruposhi mangrove plantation was dominated by two species, namely *A. officinalis* and *S. apetala*, planted in 2003-05; however, it contained another seven other mangrove species (Table 1). This increased species richness indicates that this forest is getting seeds from the natural Sundarbans through tides. In addition, the nearest natural mangrove forest (the Sundarbans) includes 24 tree species within 18 genera [55], whilst we observed nine tree species within five genera, denoting that after 15 years, this young mangrove plantation has already reached almost ~38% of natural mangrove species richness with planting only two pioneer species. Therefore, this mangrove plantation can be considered as a nature-based solution for increasing and conserving biodiversity. Besides, replacing the current two-species planting practices with multiple species [56] may improve stand structure and species diversity faster [13], as a diverse stand facilitates the occurrence of other taxonomic groups (e.g., epiphytes) and thus increases overall biodiversity and ecosystem functions [57,58]. Coastal plantations play a critical role in their surrounding aquaculture. For example, a recent study in the same region observed that litterfall of *A. officinalis, S. apetala, S. caseolaris*, and *Heritiera fomes* strongly enhances the growth performance of shrimp post larvae [59]. Therefore, we expect mixed-species plantations close to the shrimp farm may enhance the overall productivity of shrimp. However, we were unable to observe other functional groups such as epiphytes, vertebrates. As a result, we recommend that future biodiversity and ecosystem service-based studies should include diverse functional communities in order to provide a comprehensive comparative understanding of planted forest biodiversity and functions in comparison to natural forest.

The present study revealed that high exposure to the tidal water and waves, salinity, soil type, and moisture content [42] might restrict the dominance of other large mangrove species on the riverward site (Fig. 2). Soil structures in the landward site were more established and harder than in the riverward area, which might have helped to grow and hold larger trees in the landward site. Moreover, the landward site is much more subjected to allochthonous input from the surrounding shrimp farming. In contrast, the riverward soil was softer and muddier than the landward site due to the sediment deposition during high tide, which is much more suitable for seed anchoring for the pioneer species to survive and we also found higher regenerations in riverside (Table 1). Thus, the riverward site is considered an early successional stage, while the landward site is a late successional stage.

The current study found the impact of zonation or spatial distribution on species composition of mangrove species along with structural parameters such as density, basal area, H, and $D_{1.3m}$ (Tables 1–3). Njana [29] explained that species composition and structural parameters vary at specific forest sites due to differences in physiochemical properties. The differences in species composition might have happened due to local biogeochemistry such as tidal, sediment impacts [60], and sea-level changes [61], which might influence the tidal level in this region. The stand density of this young mangrove plantation at Satkhira, Bangladesh, ranged from 1400 to 1950 ha^{-1}, which was lower than mature riverine mangrove stands (917-3310 ha^{-1}) in French Guiana, reported by Fromard et al. [62]. They found higher densities in pioneer stage rather than mature stands, which is consistent with our results, as we found higher densities in the riverward site where the successional process is taking place, and the landward side is comparatively mature than the riverward forest. The present range of density was higher than that reported for the density (812 stems ha^{-1}) of mature mangrove stands in Ranong, Indonesia [63]. This study observed small-sized trees with higher density dominating communities in the riverward area, while communities in the landward area were dominated by large-sized trees with lower density (Table 2, Fig. 2). It might happen due to easy access to seed sources from the adjacent Sundarbans mangrove forest along with the chance of new land formation in the riverward area as a large number of seeds were observed in newly formed grassland on the bank of the river during the survey. *S. apetala* had occupied dominance in both regions, the presented *IV* value was higher than the dominant mangrove species of the Andaman Islands, India (*IV*=48.7~88.4) as observed by Padalia, Chauhan, Porwal and Roy [64]. This *IV* value was also comparable with the dominant mangrove species (*IV*= 69.3 ~ 61.1) on the northwestern coast of Sri Lanka as reported by Perera, Amarasinghe and Somaratna [65]. The present study's findings disclosed that mangrove plantation is miscellaneous in species composition and abundance, as it is exposed by several indicators of diversity, such as new regeneration (Table 1), envisaging a promising future for this forest.

4.2. Aboveground biomass carbon (AGC)

The current study indicates that the spatial or zonation pattern has significantly affected the carbon stock of this plantation (Table 4). We observed that aboveground carbon in the landward site is significantly higher than in the riverward (Table 4). It possibly happened due to the presence of less large-sized trees in the riverward site. This results, however, is contradicted with the results of Son et al. [40], while they pointed out that carbon stock in the Qatar mangrove decreases with increasing onward distance. In contrast, de Jong et al. [41] found seaward has no significant impact on aboveground carbon at Lindi in Tanzania.

The mean total biomass carbon (49.1 Mg C ha^{-1}) was nearly four times higher than the mangrove in Florida, USA (13.1 Mg C ha^{-1}) [66] and lower than the *Avicennia marina* dominated mangrove forest at Sofala Bay, Mozambique (61.8 Mg C ha^{-1}) [27] and the mixed mangrove forest in mainland Tanzania (73.5 Mg C ha^{-1}) [29]. The range of the present AGC (34.4 ~ 40.1 Mg C ha^{-1}) value was within the range of the presented range of AGC in the Sundarbans, India (11.1~55.4 Mg C ha^{-1}) [67] and another study in the same mangrove forest (17.3 ~ 45.4 Mg C ha^{-1}) by Ray et al. [68]. The AGC range of the current study is also within the range of mangroves at Lindi in Tanzania (11~55 Mg C ha^{-1}) [41]. The observed carbon storage in the riverward was lower than in the landward site, where the stem density was much lower than in the riverward site. However, the higher mean diameter in the landward signifies that the bigger dominant trees might cause higher AGC in the landward zone according to the "biomass-ratio hypothesis" [69]. Grime [70] also observed that the variation of the aboveground biomass was significantly correlated with the size of the trees. Besides, in the riverward areas, trees are constantly engaged in conflicting of tidal actions and may have an unstable substrate for nutrient uptake [71] or be subjected to higher salinity [72].

In addition, plantations age has a significant impact on aboveground carbon (AGC) stocks. For example, AGC of 19.3, 21.7, and 25.7 Mg C ha^{-1} were observed at ages of 10, 11, and 12, respectively, in *R. mucronata* planted mangrove forest at Lingayen Gulf, Indonesia, which are significantly lower but AGC in the 17-year planted forest (50.9 Mg C ha-1) was significantly higher [73] than our studied 15-year old planted forest (see Table 5). Similarly, a same-aged (15-year old) plantation mangrove with five species showed higher carbon stocks (62.77 Mg C ha-1) in Mahandi mangrove, East Coast, India [74]. In addition, a 15-year plantation of *S. apetala* in Qi'ao Island, China accumulated several times higher above-ground biomass [75]. In the southern coast of Bangladesh, a recent study found much lower above ground biomass stocks (14. 8 Mg ha^{-1}) after 10 years [13], while they observed that after 42 years of plantations stand structure may become identical to natural forest.

The mean carbon stock of this study area was lower than some of the stand types in the Sundarbans natural mangrove (Table 5) and this difference might have occurred due to stand age, species composition, and variation in biogeochemistry of the soil [76,77]. However, almost similar carbon stocks indicate the potentiality of young mangrove forests (15 years old) in capturing carbon from the atmosphere. Compared with the previous research, it implies that the biomass productivity of the present mangrove plantation forest is comparatively higher or identical with that of the tropical and subtropical mangroves. Soil attributes such as salinity, nutrients, and organic matter are considered the determinants of mangrove forests' stand structure, whereas forest structure has a considerable impact on productivity and the carbon cycle [78,79].

However, our observed young mangrove (i.e., 15 years of plantation) is comparable to a natural mangrove in terms of species richness and carbon stock. Therefore, more plantations in the coastal belt with multiple species may become identical to a natural mangrove forest and may reduce pressure on natural forest. As a result, mangrove plantations can be considered as a strong measure of nature-based solutions for climate change mitigation in this region, and their protection may help to fulfil the objectives of reducing emissions from deforestation and forest degradation (REDD+) [82].

4.3. Belowground root carbon (BGRC)

Our study revealed that root carbon stock was significantly influenced by sites (Fig. 3). The current study is the first study to depict the root biomass carbon (BGRC) and its diameter-wise contribution to carbon stock in the young mangrove plantation in Bangladesh. Moreover, this study revealed that the first 20 cm is the most active layer for root biomass as BGRC stock declined sharply with depth after 10 cm (Fig. 3 A, B). The present study also showed that the abundance of the coarse root ($\geq$ 5 mm in diameter) in the RMP forest is comparable to that of the consequences of Adame et al. [83]. They also observed that the coarse root class ($\geq$ 5 mm diameter) was the dominant size class in the Celestun coastal lagoon, Yucatan Peninsula, Gulf of Mexico. The present

Table 5
Comparison of carbon stock of the RMP with the Sundarbans natural mangrove forest.

Site	Salinity	Species or stand type	Carbon (Mg C ha^{-1})		References
			Aboveground	Root	
RMP	High	*S. apetala* and *A. officinalis*	37.3	11.8	This study
Sundarbans	Low	*Mixed*	162	90	Ahmed et al. [16]
Sundarbans	Medium	*Mixed*	122	77.7	Ahmed et al. [16]
Sundarbans	High	*Mixed*	99.7	71.6	Ahmed et al. [16]
Sundarbans	Low	*A. officinalis*	76.8	41.1	Kamruzzaman et al. [80]
Sundarbans	Medium-high	*Ceriops decandra* and *Excoecaria agallocha*	45.2	11.7	Rahman et al. [81]
Sundarbans	Low	*Heritiera fomes*	152.5	62.4	Rahman et al. [81]

investigation found a significant and positive relationship between BGRC and tree density and basal area (Fig. 4). The results of this study revealed consistency with the outcomes of Komiyama et al. [84] and López et al. [85]. They observed that root biomass production was manipulated and influenced by stand structure, i.e., if tree density increases, ultimately competition increases, which forces them to produce numerous roots and fine roots to acquire limited resources, which is also evident in the mangroves in Australia [26] and the Dominic Republic [86].

These findings support the resource-ratio hypothesis, which predicts that plants invest more in limited resources by optimizing other processes; therefore, mangrove typically produced high root-to-shoot (R: S) ratios to capture more nutrients in stressed condition such as high tree densities and increased salinity [3,87]. Besides, variation in root carbon stock in the study area explains the impacts of stand structure, species composition, and zonation or site on root carbon stock.

Moreover, higher density stands forces trees to produce more roots in the plantation forest [3]. The current findings are consistent with previous findings that mangrove plantation can typically cope with a saline environmental stress, a dry condition that is defined by physiologically direct waves, and oxygen deficiency by budgeting energy on producing significant proportions of roots [88,89]. Although we measured only roots up to 20 mm, our results showed that a large and considerable portion of the biomass is allocated to the belowground parts of the mangrove communities to adjust to the harsh environmental conditions. However, the study recognizes the limitation of not investigating the root carbon below 40 cm and total soil carbon from the sediments. Future research should focus on the detailed belowground carbon inventory to explore the contribution of planted mangroves to the blue economy and support the climate change mitigating process.

Although our initial baseline study only focused on single young mangrove plantations and did not include soil organic carbon, future research could focus on belowground soil carbon along the coastal belt across site, productivity, and salinity gradients to predict the future sequestering capability of restored and afforested mangroves.

4.4. Implications of the study

Coastal mangroves have long played an important role in protecting local communities and reducing losses from cyclones by buffering wind speed [90], as well as aiding climate change by absorbing carbon from the atmosphere. Although coastal plantations are largely protecting coastal localities from natural hazards, our work demonstrates that young mangrove plantations (i.e., 15-year-old) have the capacity to store almost identical carbon in their substrate to natural forest, which is promising for climate change mitigation in addition to their main intended use. As a result, more plantations along the coast may not only provide protection against natural disasters but can also serve as store house of above ground, roots and organic carbon. It may also protect the exposed coast from soil erosion, such as riverward or seaward sites. Practically, riverward sites are more feasible for plantations due to the availability of seeds that disperse through water, which may further reduce the plantation's cost. In addition, the conservation of these types of sparse vegetation and plantations can be used for ecotourism and subsistence for the local people as mangroves have potential value for ecotourism [91]. A SWOT (strengths, weaknesses, opportunities, and threats) based analysis of ecotourism in mangrove forest of Indonesia showed mangrove forest create an appealing ecotourism hub [92] that may be sustainable by incorporating the local community [93]. As such, the incorporation of local people with coastal plantations may provide ample opportunity for sustainable ecotourism in these sparse coastal vegetated areas. This will ultimately reduce the anthropogenic pressures on the natural mangroves. Furthermore, mangrove afforestation outside natural counterpart can provide similar ecosystem services such as riverbank protection, reducing erosion, trapping allochthonous pollutants such as plastics, providing products such as food, wood fuel, seeds for raising nurseries, sequestration of carbon. For example, *S. apetala* is a well-known and valuable species for food, medicine, and habitat for fish (e.g., litterfall enhances fish growth). Besides, by reducing water inflow speed (29~92%), *S. apetala* forest provided the best protection from seawater rise among other mangrove species [94]. Similarly, we believe that this *S. apetala* dominated young planted forest benefits the local community by providing storm protection, food, fuelwood, reducing river and soil erosion, and aiding in higher shrimp production. The present study only considered carbon sequestration and biodiversity conservation values of young mangrove plantations. Therefore, much research are required to understand the other ecosystem services by these mangrove plantations

Bangladesh needs reliable estimates of GHG emissions and related uncertainties from all sectors, including forests, to meet the criteria of these international policy frameworks. As, Bangladesh is committed to produce reports on greenhouse gas (GHG) emissions and anticipated scenarios as a substantial contributor to the UNFCC (United Nations Framework Convention on Climate Change) and as part of the Nationally Determined Contributions (NDCs) [2,95]. Therefore, incorporating data on carbon storage and sequestration capacity from young plantations could aid in establishing a more detailed knowledge of projected contributions to GHG emissions and reductions.

5. Conclusion

This study demonstrates that planting mangroves within 15 years increased species richness and carbon stock of the Rupashi Mangrove Plantation (RMP) in Bangladesh which signifying the potentiality of young mangrove forest in terms of mitigating climate change by accumulating carbon as biomass in above- and belowground components. The forest structure and root carbon are also significantly varied among riverward and landward sites denoting the necessity of considering spatial dynamics in young mangrove research. The outcomes of this study have practical implications in terms of adopting the policy for restoration and mangrove plantation in mitigating the effects of climate change. As this young mangrove plantation had a significant amount of carbon stock in both aboveground and belowground, similar in many parts of the Sundarbans and even higher than the polyhaline sites. This indicates that the carbon estimation in both the above and belowground of mangrove plantations also has immense importance in the global carbon budget for its higher carbon sequestration rate, especially in the belowground, indicating the ecological significance of young mangrove plantations. Therefore, we expect policy on incorporating young mangrove plantations into GHGs emission estimation will help to understand the overall contribution of young mangrove plantations to the country's total GHGs emissions and reductions.

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Declaration of Competing Interest

The authors announced that they have no contending interests.

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