Scientific Research Publishing

Open Journal of Forestry, 2024, 14, 98-116
https://www.scirp.org/journal/ojf
ISSN Online: 2163-0437
ISSN Print: 2163-0429

Impact of Planted Mangrove Species on Biomass Carbon and Other Structural Attributes in Ayeyarwady Region

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How to cite this paper: Tun, A. W., & Aye, W. N. (2024). Impact of Planted Mangrove Species on Biomass Carbon and Other Structural Attributes in Ayeyarwady Region. *Open Journal of Forestry, 14,* 98-116.
https://doi.org/10.4236/ojf.2024.141007

Received: October 31, 2023
Accepted: January 28, 2024
Published: January 31, 2024

Abstract

This study examines the impact of different mangrove species on the structure and carbon storage potential of mangrove stands in Myanmar. We focused on three species: *Avicennia officinalis*, *Avicennia marina* and *Bruguiera sexangula*. These species were selected for their fast growth, ability to protect against cyclones, and effectiveness in coastal defense during mangrove restoration. To collect data on tree structure and carbon storage, we conducted field surveys measuring parameters such as diameter at breast height (DBH), tree height and crown diameter for each tree. Non-destructive methods were used for data collection. Using ANOVA and post-hoc multiple comparison tests, we assessed differences in structure and carbon stock among the three species. Regression analysis was also performed to understand the relationship between carbon stock and structural attributes. In terms of stand densities, we observed variations among species, with pioneer stage plantations exhibiting higher densities compared to mature stands. Seedlings showed sufficient regeneration, supporting the sustainability of the forest. Biomass accumulation varied across species, with *A. officinalis* having the highest average biomass. Aboveground biomass showed a strong correlation with basal area. *A. officinalis* had the highest total biomass carbon accumulation at 55.29 ± 20.91 Mg C ha^{-1}, with 77.43% aboveground carbon and 22.57% belowground carbon. *A. marina* stored 41.09 ± 11.03 Mg C ha^{-1}, with a similar distribution of 76.05% aboveground and 23.95% belowground carbon, while *B. sexangula* stored 23.23 ± 3.12 Mg C ha^{-1}, with 70.70% aboveground carbon and 29.30% belowground carbon. The amount of aboveground carbon was a significant portion of the overall carbon storage and correlated with tree density, diameter, basal area and height. Our findings highlight the importance of selecting suitable species and considering structural attributes for mangrove restoration and carbon storage efforts. These results provide valuable insights for managing mangrove plantations at regional and global levels. On average, the reported carbon sequestration was 154.40 $MgCO_2$-eq ha^{-1}.

Keywords

Species Selection, Biomass, Carbon Storage, Ayeyarwady Region, Myanmar

1. Introduction

Mangroves are important for biology, ecology, economy, and protection. They help mitigate climate change by absorbing and storing carbon. Although they cover less than 1% of the world's forested area (Giri et al., 2011), they efficiently store significant amounts of carbon in both above- and belowground biomass. In Myanmar, there are approximately 452.958 thousand hectares of mangrove forests supporting 34 true mangrove species. Two of these species, *Sonneratia griffithii* (Critically Endangered-CR) and *Heritiera fomes* (Endangered-EN) are classified as threatened according to the IUCN Red List. Before Cyclone Nargis in 2008, the dominant species in Ayeyarwady and Yangon regions were *Excoecaria agallocha* L. and *Heritiera fomes* Buch., while *Rhizophora mucronata* Lamk. and *Rhizophora apiculata* Bl. dominated other regions (Aung et al., 2011). However, natural disasters and human activities have caused changes in the community patterns of mangrove species (Aung et al., 2013). Observations over five years following Cyclone Nargis showed an increase in recovery pathways for *Avicennia officinalis*, *Bruguiera sexangula*, and *Sonneratia caseolaris*, while *H. fomes* and *R. apiculata* populations declined. *R. apiculata* populations were mainly replaced by colonies of *A. officinalis*, which also demonstrated the highest vegetation reproduction capacity and sprouting ability compared to other species (Aung et al., 2013, Ono& Fujiwara, 2004). According to Tomlinson (1986), mangrove species from the Rhizophoraceae family lose the ability to produce reserve meristems early on, while other common genera like Avicennia, Laguncularia, and Sonneratia retain reserve meristems and develop epicormic sprouts when damaged. Pioneer mangrove species with highlight requirements can produce abundant sprouts after natural disturbances. Understanding the carbon storage potential of different mangrove species is vital for effective conservation and sustainable management strategies.

Mangroves are facing significant threats due to deforestation and degradation. The global mangrove cover has decreased by 35% between 1980 and 2000 (Valiela et al., 2001). In Myanmar, the mangrove forest cover has experienced a net loss of 35.75% from 1980 to 2020, totaling 253.040 thousand hectares. Although there have been some gains amounting to 26.753 thousand hectares, the overall net loss is 278.613 thousand hectares. The average annual deforestation rate is approximately 6.97 thousand hectares per year, equivalent to around 0.98% of the annual deforestation rate. Coastal areas and river deltas, like Ayeyarwady, are particularly affected by agriculture (rice paddies), aquaculture (shrimp farming), unsustainable fuelwood collection, and coastal development activities. The loss of mangrove forests has negative impacts on local ecosystems and the provision of ecosystem services (Bhomia et al., 2016). Proper management of mangroves is crucial, considering the invaluable services provided by these ecosystems. Zhao et al. (2004) highlight that the services provided by ecosystems and their values are site specific, and it is preferable to determine the nature and value of ecosystem services on a small scale.

This study aims to measure the carbon storage potential of the three dominant mangrove species in the Ayeyarwady Region of Myanmar: *Avicennia officinalis*, *Avicennia marina* and *Bruguiera sexangula*. Avicennia species, including these three, are widely distributed across various tropical and subtropical regions including India, Bangladesh, Brunei, Cambodia, Indonesia, Malaysia, Myanmar, Papua New Guinea, the Philippines, Singapore, Sri Lanka, Thailand, and Vietnam (Tomlinson, 1986). In the Ayeyarwady Region of Myanmar, mangrove trees including the Avicennia species hold significant value in the fisheries industry. They are utilized as fuelwood in fish processing and for constructing fishing gear, particularly rafts. However, excessive timber extraction has led to the degradation of mangrove forests. Aye & Takeda (2020) and Thatoi et al. (2016) stated that the wood from the Avicennia plant is commonly utilized for flooring and as fuel. These mangrove species thrive naturally in areas classified as inundation class 2 (elevations of 1.7 - 2.0 m asl) and class 3 (elevations of 2.0 - 2.3 m asl) based on Watson (1928) classification. Webb & Than (2000) observed that *A. officinalis* exhibits high survival and growth rates in higher elevation areas with arid and harsh environments characterized by high salinity levels. Each plant species has specific environmental tolerance, and a combination of environmental factors determines their natural distribution (Waring & Major, 1964).

2. Materials and Methods

2.1. Description of Study Site

The Ayeyarwady Delta is located in southern Myanmar, between latitudes 15˚ and 18˚N, and longitudes 94˚ and 96˚E. It receives an annual rainfall of over 3233 mm. Based on data from the Methodology Department covering the period from 2000 to 2021, the average minimum and maximum temperatures are approximately 22.6˚C and 27.95˚C, respectively. The soil in the region is mostly clay and clay loam, except in sandy ridges. When rice fields are abandoned, the soil becomes acidic, with a pH range of 5.0 - 5.5, as identified by Kogo (1993). The land elevation is low, resulting in flooding in most areas during spring tides in the rainy season and, in some areas, during equinoxial tides in the dry season. The delta experiences semi-diurnal tides with two high and low tides each day. As the study site, Wa Gon village in compartment 56 of the Pyindaye Mangrove Reserved Forest (PMFR) in Pyapon township (**Figure 1**) was chosen.

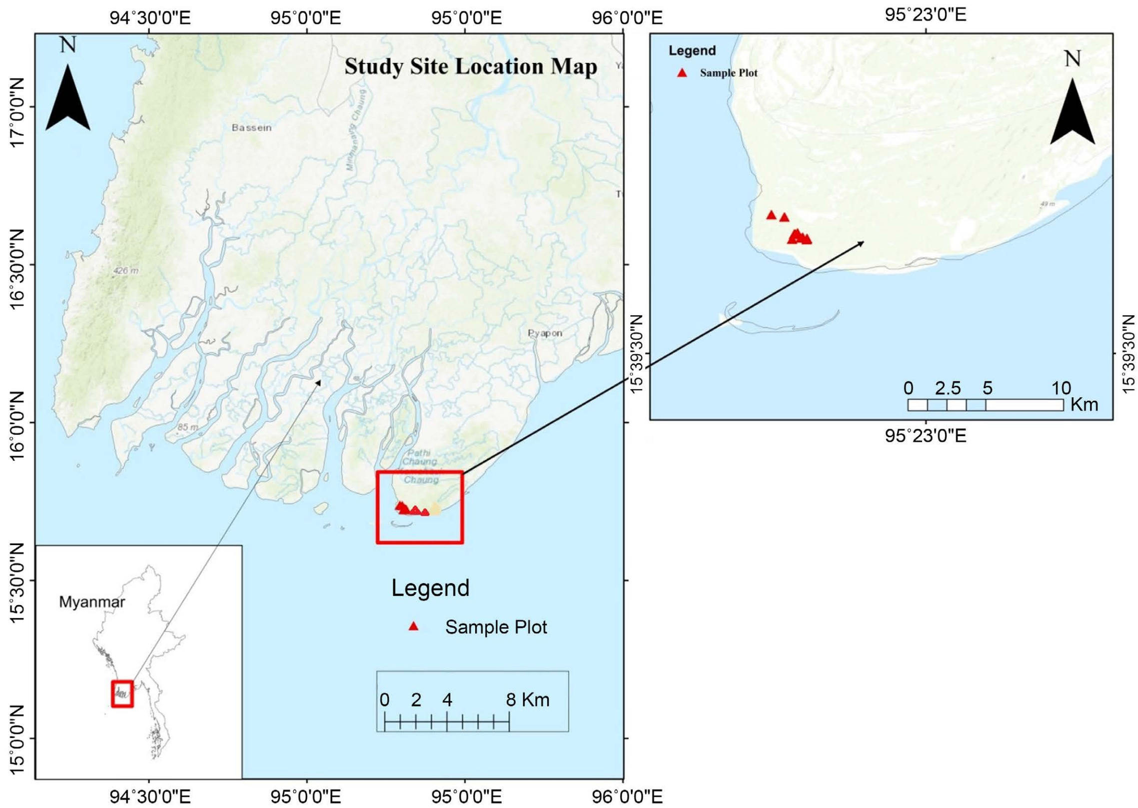


Figure 1. Location of the study site.

A notable characteristic of the delta is the presence of permanent settlements within the forest reserve. People live in villages within and around the delta, relying on mangroves and associated resources such as fisheries and agriculture for their livelihoods. The mangrove ecosystem in the delta plays a vital role in providing socio-economic benefits, including rice farming, the utilization of mangroves for poles and timber and fishing for both food and income security. Rice farming in the delta involves clearing mangroves to create space for cultivation. Additionally, charcoal made from mangroves in the Ayeyarwady Delta is supplied to local markets in nearby cities and towns, particularly Yangon city (JICA, 2005).

2.2. Field Survey and Statistical Analysis

The fieldwork for this research was conducted in July 2021, focusing on plantations dominated by *A. officinalis* (6 plots), *A. marina* (5 plots) and *B. sexangula* (5 plots). These plantations were established using potted seedlings in plastic bags measuring 17.8 cm × 7.6 cm, obtained from the nursery. The standard spacing between seedlings in the afforestation program in this area was 1.8 m × 1.8 m. Within each plantation, random 20 m × 20 m plot quadrants were selected, and mangrove trees with a stem diameter greater than 5 cm (DBH ≥ 5 cm) were identified and counted in each quadrant.

The study recorded the number of mangrove plants by species and calculated the total number of planted mangrove trees in each plot based on the planting density in Ayeyarwady Delta. The survival rate of the planted mangroves was estimated using Equations (1) and (2), and the results were used to determine the number of trees per hectare. Natural regeneration of mangroves outside the planted rows and columns within the plots was also considered as part of the overall regeneration.

$$\text{Density of species}\left(\text{No}\cdot\text{ha}^{-1}\right)=\text{Number of individual species}\times\frac{10000\ \text{m}^2}{\text{Area of plot}\left(\text{m}^2\right)} \quad (1)$$

$$\text{survival}=\frac{\text{number of remaining plants}}{\text{number of plants originally}}\times 100(\%) \quad (2)$$

Within the main plot of 20 m × 20 m, five smaller plots measuring 5 m × 5 m each were selected to assess natural regeneration (NR) stands. The diameter at breast height (DBH) and height (H) of all trees in small plots were measured and recorded. The densities of saplings of different species were determined and categorized into diameter classes, taking into account the average length of propagules. This classification included seedlings (0 - 50 cm) and saplings (51 - 150 cm). The ratio of seedlings, saplings, and trees was used to evaluate the adequacy of natural regeneration, following the methodology outlined by FAO (1994). The presence or absence of grasses, climbers, and shrubs in each 2 m × 2 m quadrant was also recorded.

The study analyzed the structural characteristics of the stand, including tree height, stem diameter, mean stand density, mean sapling density, mean regeneration density, and mean basal area. These variables were checked for normality and normalized if necessary. Tree basal area, stand density, and frequency were calculated based on the methods established by Cintron & Novelli (1984). Stand densities and survival rates were measured and calculated by species for each plot.

Estimating Biomass and Carbon Accumulation

In this study, we used site-specific allometric equations developed by Thant et al. (2012) to estimate above- and below-ground biomass. These allometric equations based on sample trees from the mangrove plantation in the Ayeyarwady Region in Myanmar, as described in Equations (3) and (4). These equations have a high coefficient of determination (r^2) of 0.99 and 0.98. It is important to note that a coefficient of determination (r^2) of 0.99 and 0.98 indicates a strong correlation, although it may not reach 100 due to inherent variability or model limitation. Here, we considered only trees with a DBH ≥ 5 cm for biomass estimation.

$$W_{\text{AGB}}=0.22\times\varrho\times\left(\text{DBH}^2H\right)^{0.82} \quad (3)$$

$$W_{\text{BGB}}=1.69\times\varrho\times\left(\text{DBH}^2H\right)^{0.40} \quad (4)$$

where: AGB is the above-ground biomass in kg per tree, DBH is diameter at breast height in cm and BGB is below-ground biomass in kg per tree. ϱ represents the wood density of the species.

The wood density values of different mangrove species were determined based on the study by Thant et al. (2012). The specific values for wood density were as follows: *Avicennia officianlis* (0.515 ± 0.021) (×10^3 kg/m^3), *Avicennia marina* (0.556 ± 0.515) and *Bruguiera sexangula* (0.531 ± 0.011). To calculate the carbon mass above and below the ground, biomass densities were multiplied by conversion factors of 0.47 and 0.39, respectively, following the guidelines of IPCC (2006). Carbon stock values were converted to carbon dioxide equivalents (CO_2-eq) by multiplying the C-stocks by 3.67 (Adame et al., 2018; Atwood et al., 2017; Hamilton & Friess, 2018).

2.3. Statistical Analysis

The analysis excluded the effect of age on stand structure, as the ages of the plantations were similar. The collected data from three planted species such as tree structure and carbon stock were used to test the hypotheses. Single-factor analysis of variance (ANOVA) was performed to analyze differences in structural parameters (mean DBH, mean H, stand basal area, and crown area) and carbon stock among the three species. The Tukey post hoc multiple comparison test was used to identify significant differences between combinations. Before conducting the ANOVA test, the data was checked to ensure it met the assumptions of normality and homogeneity of variance. Regression analysis was conducted to examine the relationship between carbon stock and structural attributes. A significant level of 95% was used in all tests, and the results were presented as mean ± standard deviation. Microsoft Excel spreadsheet and R programming (version 4.2.2) were used for data analysis.

3. Results

It presents information on the structural composition of three mangrove species: *Avicennia officinalis*, *Avicennia marina* and *Bruguiera sexangula*. It provides detailed data on their stand densities, structural attributes, biomass and carbon stock estimation.

3.1. Stand Density and Structural Characteristics

The stand density for the three planted species was as follows: 2,521 trees per ha for *A. officinalis*, 1,887 trees per ha for *A. marina*, and 1,825 trees per ha for *B. sexangula* (**Table 1**). All three species had a survival rate above 65% within 4 years, with an initial plantation density of 3,086 trees per ha and a uniform spacing of 1.8 meters by 1.8 meters. Tree diameter at breast height showed significant differences between species ($p < 0.05$). The average diameter at breast height (DBH) was 13.81 ± 2.20 cm for *A. officinalis*, 13.44 ± 0.69 cm for *A. marina*, and 10.33 ± 1.20 cm for *B. sexangula*. The average height was 4.16 ± 0.55 m for *A. officinalis,* 3.91 ± 0.52 m for *A. marina,* and 3.56 ± 0.49 m for *B. sexangula*. *A. officinalis* had the largest average DBH and height among the three species.

Table 1. Stand structural attributes for each species.

Species	Tree density (stem·ha^{-1})	Basal area (m^2·ha^{-1})	Mean DBH (cm)	Mean H (m)
Avicennia officinalis	2521 ± 472^{a}	47.89 ± 18.27^{a}	13.81 ± 2.20^{a}	4.16 ± 0.55^{a}
Avicennia marina	1887 ±552^{a}	34.10 ± 8.91^{ab}	13.44 ± 0.69^{ab}	3.91 ± 0.52^{a}
Bruguiera sexangula	1825 ± 260^{a}	19.10 ± 3.81^{b}	10.33 ±1.20^{b}	3.56 ± 0.49^{a}

Note: Values for stand structures represented the stand mean ± standard deviation. The basal area (m^2·ha^{-1}) represented the sum of the basal areas for sample plot. The alphabets of the superscript varied within the group ($p < 0.05$).

There was a positive correlation between stem diameter and height across all three species, indicating that stem diameter generally increased with height (**Figure 2**). The equation, correlation (r^2), and significance ($p < 0.05$) were provided for each case. Box plots were used to display percentile distributions, with the ends of the boxes representing the 25th and 75th percentiles of the data set. The extremities of the plot corresponded to the observed maximum and minimum values in the data set. Basal area also varied significantly between mangrove species ($p < 0.05$). The basal area measurements were as follows: 47.89 ± 18.27 m^2·ha^{-1} for *A. officinalis*, 34.10 ± 8.91 m^2·ha^{-1} for *A. marina* and 19.10 ± 3.81 m^2·ha^{-1} for *B. sexangula*.

Forest vegetation structure

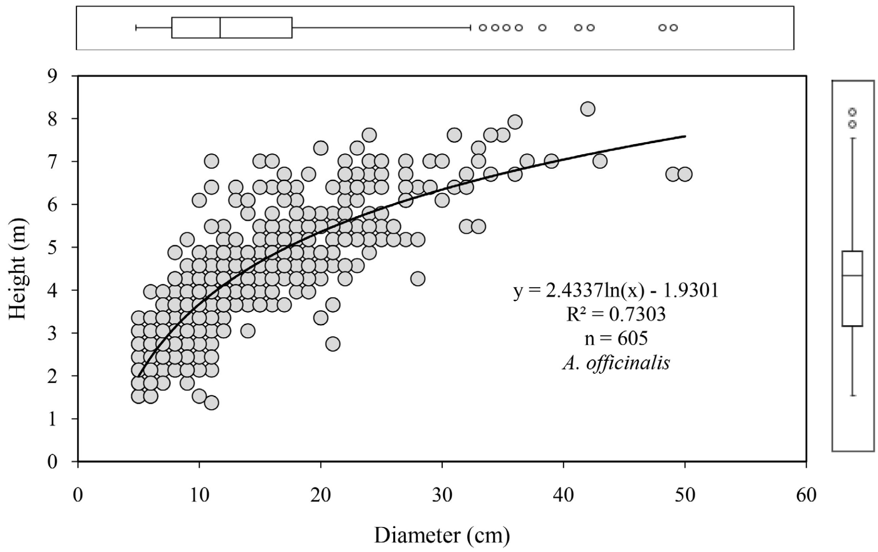
The forest vegetation structure consists of different forms of vegetation arranged in a complex manner. It can be used to determine horizontal and vertical stratification. The plantations of the three species showed a numerical dominance of young trees, with the highest stem density observed in the 5 - 10 cm diameter class (40% for *A. officinalis*, 43.18% for *A. marina* and 57.66% for *B. sexangula*). As the diameter classes increased, the density of trees generally decreased, resulting in a reversed-J shaped distribution (**Figure 3**). The relationship between diameter class and individual density revealed that larger diameter classes had lower individual densities, indicating horizontal structure (**Figure 4**). The vertical structure was characterized by combining tree density with tree height classes (**Figure 5**).

3.2. Regeneration Status of Different Species

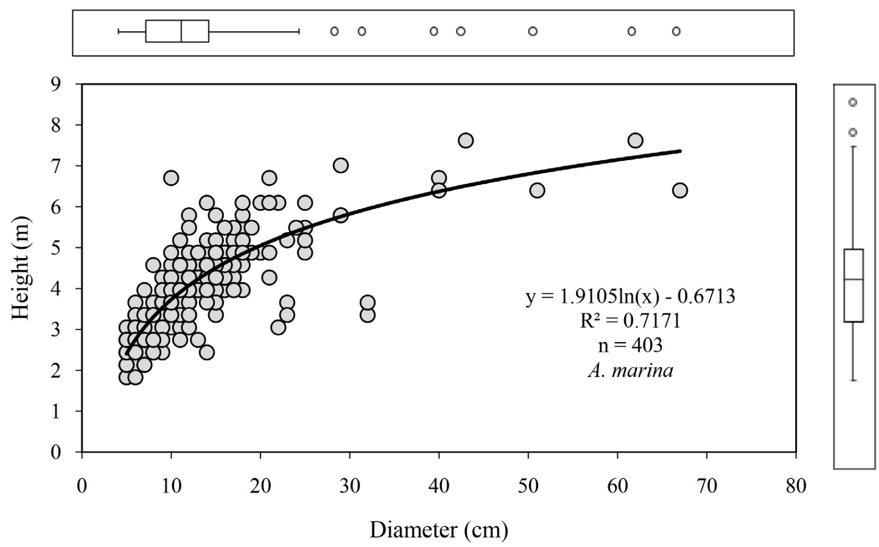
In the area where natural regeneration (NR) occurred, the overall stand density was high, with 24,776 stems per ha. Among the species present, *B. sexangula* had the highest proportion, accounting for 17,048 stems per ha or 68.81% of the total. *A. officinalis* contributed 5,241 stems per ha (21.15%) and *A. marina* contributed 2,264 stems per ha (9.14%) (**Table 2**). The dominance of young *B. sexangula* trees was clearly observed within the natural regeneration area. Other mangrove tree species such as *B. gymnorhiza* (0.74%), *Heritiera fomes* (0.07%), *Aegiceras corniculatum* (0.06%) and *Ceriops decandra* (0.04%) were also observed, but in smaller proportions.

Table 2. Density of regeneration for mangrove species.

Species	Regeneration		Density stems·ha^{-1} (%)	Ratio
	Seedling stems·ha^{-1} (%)	Sapling Stems·ha^{-1} (%)		
B. sexangula	10,811 (63.42)	6237 (36.58)	17,048 (68.81)	1:0.58
A. officinalis	4745 (67.79)	2255 (32.21)	5241 (21.15)	1:0.48
A. marina	3500 (62.90)	2064 (37.10)	2264 (9.14)	1:0.59
B. gymnorhiza	100 (54.64)	83 (45.36)	183 (0.74)	1:0.83
H. fomes	11 (64.71)	6 (35.29)	17 (0.07)	1:0.55
A. corniculatum	10 (71.43)	4 (28.57)	14 (0.06)	1:0.4
C. decandra	5 (55.56)	4 (44.44)	9 (0.04)	1:0.80
Total ha^{-1} Proportion (%)	**19,182 (64.29%)**	**10,653 (35.71%)**	**29,835**	**1:0.56**



(a)



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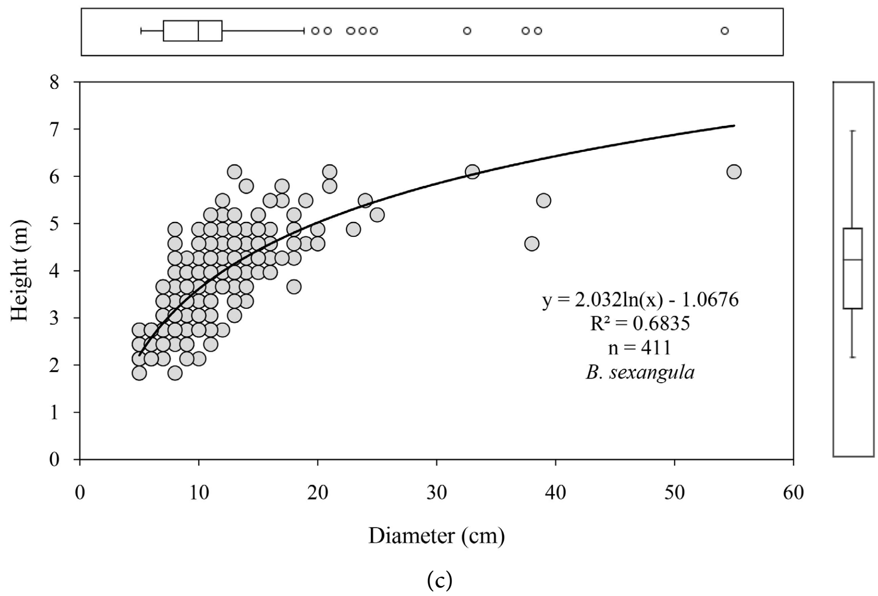


Figure 2. Scatterplots of heights against stem diameter distribution for the three species: (a) *Avicennia officinalis*, (b) *Avicennia marina* and (c) *Bruguiera sexangula*.

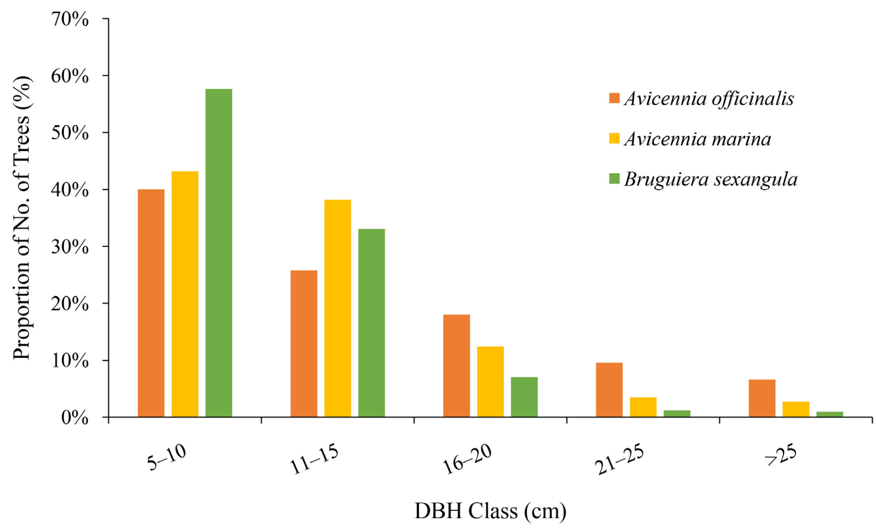


Figure 3. Density of trees in different diameter classes for three mangrove species.

The average height of the three dominant species was measured as 2.80 m for *A. officinalis*, 3.01 m for *A. marina*, and 2.84 m for *B. sexangula*. The regeneration ratios for seedling to sapling were 1:0.57 for *B. sexangula*, 1:0.72 for *A. officinalis*, 1:0.89 for *A. marina*, 1:0.83 for *B. gymnorhiza*, 1:0.55 for *H. fomes*, 1:0.40 for *Aegiceras corniculatum*, and 1:0.80 for *C. decandra* (refer to **Table 2**). There were 15,178 stems per ha classified as seedlings and 9,598 stems per ha classified as saplings. The density of seedlings was higher than that of saplings, indicating a promising potential for future plantations (refer to **Figure 6**). *A. officinalis*, *A. marina* and *B. sexangula* plantations also contained various grasses, climbers, herbs, ferns and shrubs. Furthermore, the natural regeneration of four non-planted tree species, namely *Aegiceras corniculatum*, *Bruguiera gymnorhi-*

za, *Ceriops decandra*, and *Heritiera fomes*, was observed in all three plantations (refer to Table 3).

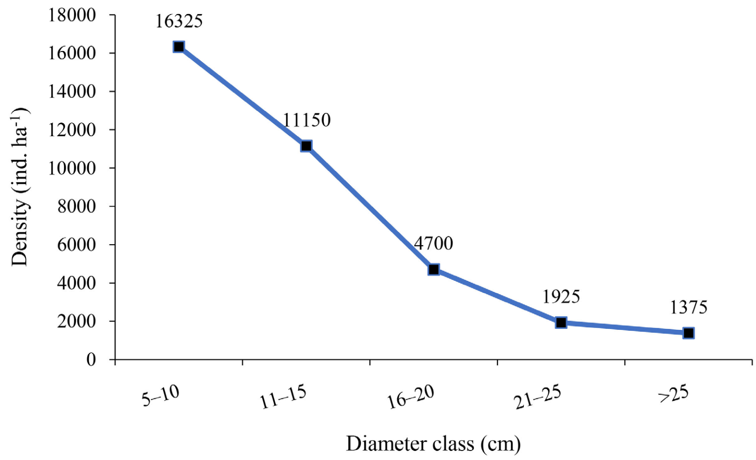


Figure 4. Horizontal structure across different diameter classes.

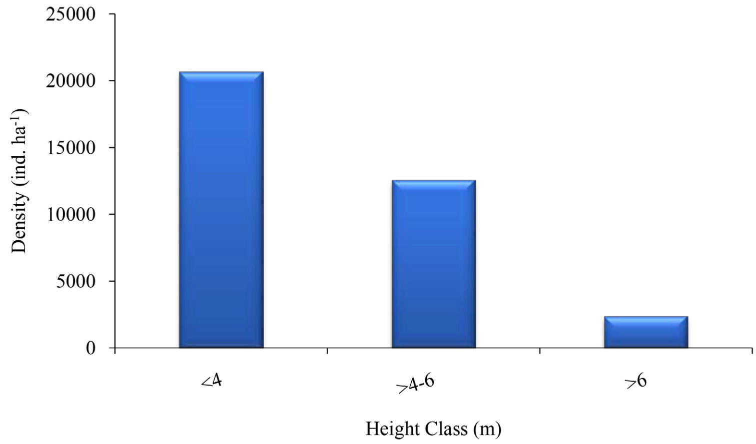


Figure 5. Vertical structure in several height classes.

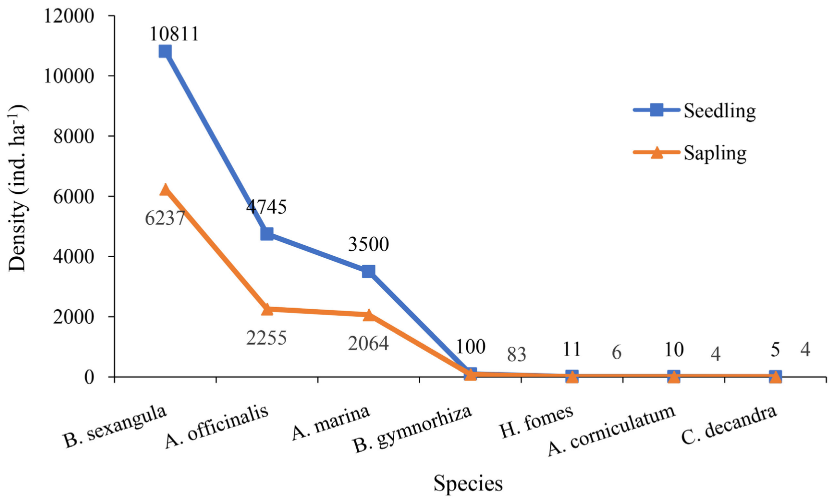


Figure 6. Reverse J-shaped distribution curve.

Table 3. Regeneration conditions at the three plantations of study sites based on field observations of species presence.

Family	Species	Local name	Type
Poaceae	*Paspalum vaginatum*	Myat-khar	Grass
Fabaceae	*Derris trifoliata Lour.*	Nwenet	Climber
Acanthaceae	*Acanthus ilicifolius*	Khaya-kayan	Herb
Acanthaceae	*Acanthus ebracteatus Vahl*	Khaya-phyu	Herb
Leguminosae	*Dalbergia spinosa Roxb.*	Su-gote	Herb
Pteridaceae	*Acrostichum speciosum*	Hnagt-gyi-taung	Fern
Arecaceae	*Phoenix paludosa*	Thin-baung	Shrub
Avicenniaceae	*Avicennia officinalis*	Thame-gyi	Tree
Avicenniaceae	*Avicennia marina*	Thame-phyu	Tree
Primulaceae	*Aegiceras corniculatum*	Ye-kaya	Tree
Rhizophoraceae	*Bruguiera gymnorhiza*	Byu-oak-saung	Tree
Rhizophoraceae	*Bruguiera sexangula*	Byu-shwe-war	Tree
Rhizophoraceae	*Ceriops decandra*	Ma-da-ma	Tree
Rhizophoraceae	*Heritiera fomes*	Ma-da-ma	Tree

3.3. Biomass and Carbon Accumulation Estimates

There were significant differences in biomass and carbon accumulation estimates among the mangrove species ($p < 0.05$). *A. officinalis* had the highest aboveground biomass accumulation, averaging 91.09 ± 37.88 Mg·ha^{-1} (range: 49.49 - 152.53 Mg·ha^{-1}). *A. marina* followed with 66.48 ± 18.62 Mg·ha^{-1} (range: 50.36 - 87.52 Mg·ha^{-1}) and *B. sexangula* showed the lowest accumulation at 34.94 ± 5.75 Mg·ha^{-1} (range: 28.49 - 42.00 Mg·ha^{-1}). Similarly, belowground biomass accumulation was highest in *A. officinalis* with a mean value of 31.99 ± 8.26 Mg·ha^{-1} (range: 21.23 - 45.07 Mg·ha^{-1}), followed by *A. marina* with 25.24 ± 8.64 Mg·ha^{-1} (range: 18.22 - 37.77 Mg·ha^{-1}), and *B. sexangula* with 17.45 ± 1.51 Mg·ha^{-1} (range: 15.39 - 18.99 Mg·ha^{-1}). When considering the total biomass accumulation (above- and belowground), *A. officinalis* had the highest value at 123.08 ± 45.85 Mg·ha^{-1} (range: 70.72 - 197.61 Mg·ha^{-1}), followed by *A. marina* at 91.71 ± 24.61 Mg·ha^{-1} (range: 71.91 - 125.29 Mg·ha^{-1}) and *B. sexangula* at 52.39 ± 6.94 Mg·ha^{-1} (range: 43.89 - 59.94 Mg·ha^{-1}) (refer to Table 4).

The aboveground-to-belowground (AGB:BGB) ratio was 1:2.76 for *A. officinalis*, 1:2.77 for *A. marina* and 1:2.00 for *B. sexangula*. *B. sexangula* had the highest AGB:BGB ratio (1:2.00), with belowground biomass accounting for 33.91% of the total biomass. *A. marina* had a ratio of about 1:2.77, with 27.52% of the belowground biomass. In contrast, *A. officinalis* had the lowest ratio

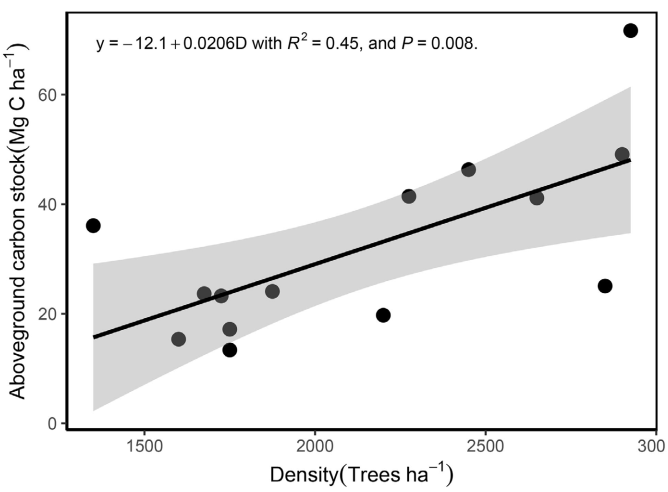
(1:2.76) with 25.99% of the belowground biomass.

Regarding carbon storage, the estimated total carbon stored and sequestered for each species were as follows: *A. officinalis* stored 55.29 ± 20.91 Mg C ha^{-1}, with 77.43% in aboveground carbon and 22.57% in belowground carbon. *A. marina* stored 42.09 ± 11.03 Mg C ha^{-1}, with a similar distribution of 76.05% aboveground and 23.95% belowground carbon. *B. sexangula* stored 23.23 ± 3.12 Mg C ha^{-1}, with 70.70% in aboveground carbon and 29.30% in belowground carbon. Overall, aboveground carbon constituted approximately 75.98% of the total carbon pool, while belowground carbon accounted for about 24.02%. Aboveground carbon showed a positive correlation with tree density (**Figure 7(a)**), tree diameter (**Figure 7(b)**), basal area (**Figure 7(c)**) and tree height (**Figure 7(d)**).

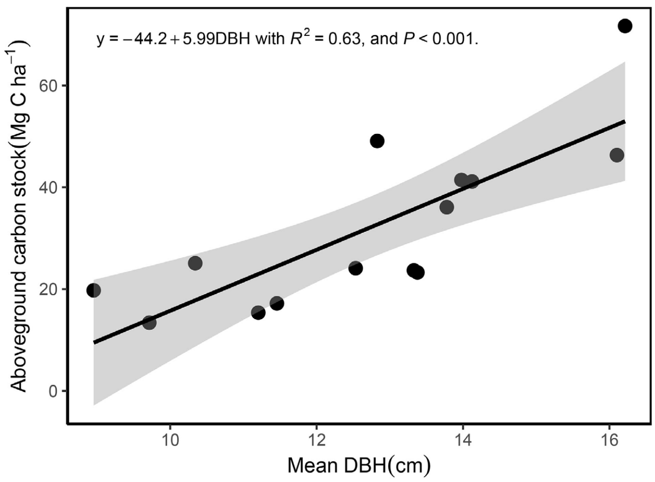
Table 4. The above and belowground biomass and carbon stock for the main tree species.

Stand	AGB ($Mg \cdot ha^{-1}$)	Range (Min-Max)	BGB ($Mg \cdot ha^{-1}$)	Range (Min-Max)	Total Biomass ($Mg \cdot ha^{-1}$)
A. officinalis	91.09 ± 37.88[a]	49.49 - 152.53	31.99 ± 8.26[a]	21.23 - 45.07	123.08 ± 45.85[a]
A. marina	66.48 ± 18.62[ab]	50.36 - 87.52	25.24 ± 8.64[ab]	18.12 - 37.77	91.71 ± 24.61[ab]
B. sexangula	34.94 ± 5.75[b]	28.49 - 42.00	17.45 ± 1.51[b]	15.39 - 18.99	52.39 ± 6.94[b]
	68.01 ± 34.96	**28.49 - 152.53**	**25.91 ± 9.12**	**15.39 - 45.07**	**93.92 ± 43.40**
	AGC (Mg C ha^{-1})	**Range (Min-Max)**	**BGC (Mg C ha^{-1})**	**Range (Min-Max)**	**Total Carbon (Mg C ha^{-1})**
A. officinalis	42.81 ± 17.80[a]	23.26 - 71.69	12.48 ± 3.22[a]	8.28 - 17.58	55.29 ± 20.91[a]
A. marina	31.25 ± 8.75[ab]	23.67 - 41.13	9.84 ± 3.37[ab]	7.07 - 14.73	41.09 ± 11.03[ab]
B. sexangula	16.42 ± 2.70[b]	13.39 - 19.74	6.81 ± 0.59[b]	6.00 - 7.41	23.23 ± 3.12[b]
	31.97 ± 16.43	**13.39 - 71.69**	**10.10 ± 3.56**	**6.00 - 17.58**	**42.07 ± 19.71**

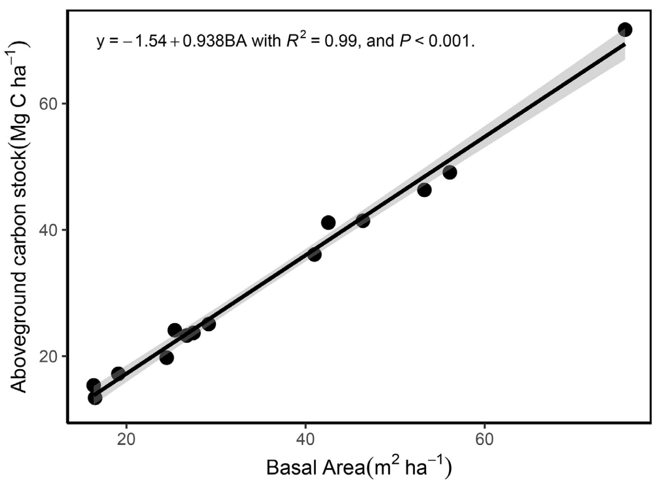
Note: Values -mean ± standard deviation. The alphabets of the superscript varied within the group ($p < 0.05$).



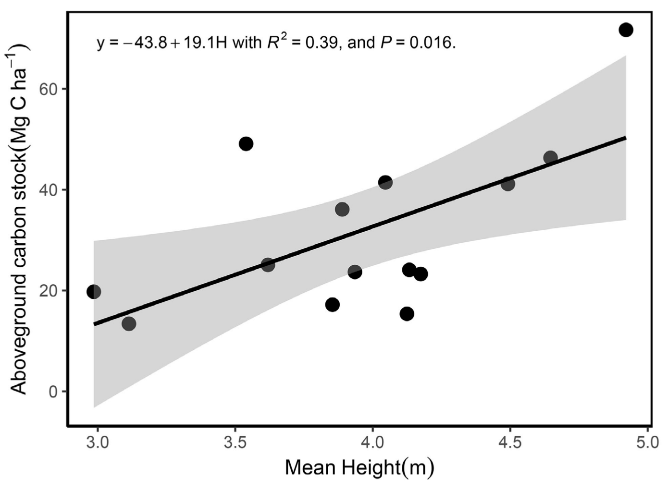
(a)



(b)



(c)



(d)

Figure 7. Relationship between plot-wise aboveground carbon stock and aboveground structural parameters: (a) Tree density, (b) Mean DBH, (c) Basal area, (d) Mean height. A 95% confidence interval is shown by the shaded area.

4. Discussion

The choice of mangrove species can affect the stand structure. Species such as *Avicennia officinalis*, *Avicennia marina*, *Sonneratia caseolaris*, and Bruguiera species have been commonly planted for mangrove rehabilitation in Myanmar since 1982. These species are favored for their fast growth, ability to protect against cyclones and other natural disasters, and quick returns in terms of coastal protection services. In this study, stand densities ranged from 1,725 to 2,925 stems·ha^{-1} for *A. officinalis*, 1,350 to 2,650 stems·ha^{-1} for *A. marina*, and 1,600 to 2,200 stems·ha^{-1} for *B. sexangula*. These densities fall within the range observed in similar forests worldwide (322 – 2,470 stems·ha^{-1}) (Jimenez et al., 1985). The current range of stand density is higher than those reported for mangrove plantations in Satkhira, Bangladesh (1,400 – 1,950 stems·ha^{-1}) (Ahmed et al., 2022). The study also found higher densities in pioneer stage plantations compared to mature stands, which is consistent with previous findings.

The stand structure of planted mangroves is influenced by factors such as tree density, species composition, biomass, and carbon storage goals. The average basal area and stem densities of the mangrove plantation were 35.73 ± 17.44 m^2·ha^{-1} and 2,141 ± 537 stems·ha^{-1}, respectively. These figures are similar to *Rhizophora mucronata*-dominated forests along the Kenyan coastline, including Mida (23.62 m^2·ha^{-1}, 1,192 stems·ha^{-1}); Kiunga (46.97 m^2·ha^{-1}, 2,142 stems·ha^{-1}) (Kairo et al., 2002); Ngomeni (33.14 m^2·ha^{-1}, 1,251 stems·ha^{-1}) (Bundotich et al., 2023); Tudor Creek (13.02 m^2·ha^{-1}, 1,145 stems·ha^{-1}) (Mohamed et al., 2009).

The number of seedlings per hectare was the highest, with 15,178 individuals per ha, indicating sufficient regeneration of the young plantation. Having more young individuals than adults ensure forest sustainability because the young population can maintain forest regeneration (Kusmana & Susanti, 2015). The overall growth pattern of the plantation resembled a reversed J-shape, indicating favorable conditions for optimal and satisfactory regeneration. According to Pandey et al. (2012), a forest is considered to have a good regeneration if there are more than 5,000 seedlings and 2,000 saplings per hectare. Chong (1988) also stated that 2,500 seedlings per ha is sufficient for natural regeneration, which is higher than the recommended level by the FAO. Therefore, this suggests a significant chance for the plantation to successfully restock the forest and undergo natural recovery.

Biomass accumulation estimates

Biomass accumulation varied among different mangrove species. *B. sexangula* had the lowest biomass accumulation at 43.89 Mg·ha^{-1}, while *A. officinalis* had the highest at 197.61 Mg·ha^{-1}, with a mean (±sd) biomass of 93.92 ± 43.40 Mg·ha^{-1}. *A. officinalis* had the highest mean biomass at 123.08 ± 45.85 Mg·ha^{-1}, followed by *A. marina* and *B. sexangula*. *A. officinalis* had a higher total biomass of 70.69 Mg·ha^{-1} compared to *B. sexangula* as well as a higher biomass of 31.37 Mg·ha^{-1} compared to *A. marina*. The difference in biomass accumulation can be attributed to variations in the structural composition of the mangroves, including stand densities. This study found a strong correlation between aboveground biomass and basal area. Basal area is commonly used as an indicator of biomass and carbon because it integrates the effects of both the number and size of trees, making it an effective predictor of biomass and carbon (Eamus et al., 2000). Komiyama et al. (2000) and Krauss et al. (2008) stated that species of Rhizophoraceae were found to be more tolerant to low nutrient conditions compared to other mangrove species. This was evident in the lower AGB:BGB ratio of *B. sexangula* compared to *A. officinalis* and *A. marina* (2.76 for *A. officinalis*, 2.77 for *A. marina* and 2.00 for *B. sexangula*). It should be noted that the ratio for *A. marina* in this study is higher than in other reports: 2.73 in *A. marina* (Kathuresan et al., 2013), 1.72 in *A. marina* (Mackey 1993).

The mean total biomass carbon was approximately 42.07 ± 19.71 Mg C ha^{-1}, which is comparable to mangroves in Bangladesh (49.1 Mg C ha^{-1}) (Ahmed et al., 2022) and lower than the *Avicennia marina* dominated mangrove forest in Sofala Bay, Mozambique (61.8 Mg C ha^{-1}) (Sitoe et al., 2014). In this study, the mean total biomass carbon of *Avicennia marina* is 41.09 ± 11.03 Mg C ha^{-1}. The range of aboveground carbon (AGC) in this study (13.39 - 71.69 Mg C ha^{-1}) was greater than that in the Sundarbans, India (11.1 - 55.4 Mg C ha^{-1}) (Mitra et al., 2011) and a study in the same mangrove forest (17.3 - 45.4 Mg C ha^{-1}) by Ray et al. (2011). The AGC range in this study falls within the range of mangroves in Lindi, Tanzania (11 - 55 Mg C ha^{-1}) (de Jong Cleyndert et al., 2020). The quantity and rate of carbon stocking in restored mangroves in Rufiji Delta varied depending on factors such as the age of the restored forest, management approach, and planted species. The carbon stocks at the ages of 5, 10, and 15 were 13.65 Mg C ha^{-1}, 20.13 Mg C ha^{-1} and 57.53 Mg C ha^{-1} respectively (Monga et al., 2022). This study found a relationship between plot-wise aboveground carbon stock and aboveground structural parameters such as tree density, mean DBH, basal area, and mean height. Among these parameters, the relationship between carbon stock and basal area showed more significance compared to other structural parameters. Grime (1998) also observed a significant correlation between the variation in aboveground biomass and tree size. Kathiresan et al. (2013) stated that the growth variables exhibited significant variation mainly between mangrove species rather than mangrove sites. This finding was supported by Komiyama et al. (2005) who found that allometric equations of mangrove species are highly species-specific but less site-specific.

5. Conclusion

In conclusion, this study provides important findings regarding the biomass of *Avicennia officinalis*, *Avicennia marina* and *Bruguiera sexangula* in the plantation of Ayeyarwady Region, Myanmar. The forests dominated by *B. sexangula* showed a higher regeneration density compared to those dominated by *A. officinalis* and *A. marina*. Overall, the number of trees and regeneration followed a reversed "J" curve, indicating satisfactory forest regeneration in all three managed forests. Natural regeneration of non-planted species was also observed, likely influenced by factors such as surrounding environments, tidal currents' strength, availability of seeds and propagules in the area and dispersal characteristics of different mangrove species.

A. officinalis trees in the plantation showed faster growth compared to *A. marina* and *B. sexangula* due to their recognized fast-growing nature. The field survey also revealed higher survival rates and greater coppicing and branching below breast height in *A. officinalis* trees compared to *A. marina* and *B. sexangula*. Additionally, *A. officinalis* displayed significant carbon storage potential in both aboveground and belowground biomass, emphasizing the important role of mangrove carbon estimation in global carbon budgeting, given their high sequestration rates.

Conserving mangroves is crucial for maintaining and expanding their presence in delta regions prone to natural hazards. Understanding mangrove vegetation structure is essential for conservation and management purposes. Afforestation of mangroves beyond natural areas offers similar ecosystem services, including protection against erosion, provision of food and fuelwood, and carbon sequestration. The seeds of *A. officinalis* and *B. sexangula* can be easily obtained near villages in the Ayeyarwady Delta. Both species can be directly sown from April to mid-September during the rainy season, which has abundant rainfall. For *B. sexangula*, propagules should be planted 1 - 2 weeks before the middle of March to enhance anchoring and survival during high spring tides in the dry season. On the other hand, *A. officinalis* seeds are available from August to September and can be sown during days with neap tides in the rainy season.

The dominance of *A. officinalis* in young plantations brings various benefits to local communities, including storm protection, a food source, fuelwood, reduced river and soil erosion, and support for increased shrimp production. It is important to note that this study primarily focused on the carbon sequestration values of mangrove species in young plantations. Further research is required to investigate other ecosystem services provided by these plantations, including soil carbon stocks, and factors such as changes in salinity and hydrological systems that could influence carbon dynamics.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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