



Biomass and carbon stocks in mangrove-afforested areas, central coastal areas of Bangladesh

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ABSTRACT

Mangroves are the remarkably productive ecosystems of the world which losses its natural existence to a great portion and presently emphasis is given on its plantation for future conservation. Thus, present study focused on the development of biomass models for the *Sonneratia caseolaris* (L.) and *Sonneratia apetala* (Buch-Ham), and assessment of carbon stock for the plantation of central coastal areas of Bangladesh. Semi-destructive approach was applied for estimating the biomass of trees. The best-fit TAGB models for *S. apetala* and *S. caseolaris* plantations were $\ln(\text{TAGB}) = -1.89 + 2.10 * \ln(D) + 0.23 * \ln(H)$, and $\ln(\text{TAGB}) = -3.09 + 2.31 * \ln(D) + 0.35 * \ln(H)$, respectively. Carbon stocks in TAGB and below-ground were estimated for a young mangrove plantation (<20 years) with *Sonneratia apetala* and *Sonneratia caseolaris*; and for an older plantation (>40 years) with *Sonneratia apetala* separately. The mean ecosystem carbon stock (above- and below-ground) of young and mature were estimated to be $350.53 \pm 14.23 \text{ t C/ha}$ and $483.64 \pm 16.35 \text{ t C/ha}$, respectively which varied significant ($p < 0.05$) between the sites. The current study recommended assessing the biomass of studied species using the site and species-specific allometric models for the correct carbon accounting.

Introduction

Mangroves are distinct and exceptionally productive ecosystems characterized by the presence of salt-tolerant plants that thrive in tropical and sub-tropical protected coasts (Duke, 2011; Md Isa and Suratman, 2021). Mangrove plant species are capable to establish dense forest ecosystems in proximity to estuaries, lagoons, and tidal flats at the tropical and sub-tropical protected coasts (Alongi, 2009). Mangrove ecosystems are distinguished by the presence of intricate root systems that extend both above and below the water surface (Harishma et al., 2020). Mangrove ecosystem offers a range of products and services and providing habitats for wide range of flora and fauna (Uddin et al., 2013).

The global extent of natural mangrove forests is estimated to be 14.8 million hectares, which is 0.364 % of the world's total forest area (FAO, 2020). Globally, mangrove forests are declining alarmingly; 1.04 million hectares of mangrove areas decreased in the last three decades. Over exploitation of forest resources, aquaculture, rapid expansion of agriculture, urbanization, industrialization and upstream pollution are the key drivers of mangrove degradation (Bhowmik et al., 2022; Cahyaningsih et al., 2022).

To halt this scenario of mangrove destruction, many countries in the

world have initiated restoration of natural mangroves and extension through the coastal afforestation programs (Uddin et al., 2022). Mangrove plantation initiatives are conducted for restoring the benefits of mangroves such as: coastal protection from erosion and tidal surges, conservation of biodiversity, climate change mitigation and carbon stock/ sequestration capacity (Osti et al., 2009; Hongwiset et al., 2022; Uddin et al., 2023). Mangroves are highly efficient at sequestering atmospheric carbon and storing it in their biomass and sediments. Globally mangroves can sequester $14.2 \text{ (Tg C yr}^{-1}\text{)}$, with a corresponding value of $1.71 \pm 0.17 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ (Alongi, 2014, 2018). Mangrove ecosystem has the ability to store carbon for long periods, especially in the dense organic-rich sediments, contributes significantly to climate change mitigation efforts. For this reason, restoration of carbon-rich mangrove ecosystems has gained special attention to mitigate climate change related problems (Macreadie et al., 2019).

Bangladesh contains extensive natural and manmade mangrove forests. Bangladesh is pioneer in coastal afforestation, which was started in 1966 with the objectives to protect life and property of the coastal people from, tidal surges and tropical cyclone and protect the accreted coastal areas (Mahmood et al., 2020a). Presently, coastal afforested areas of Bangladesh are about 2000 km^2 (FD, 2019). *Sonneratia apetala* is

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the prominent tree species in the coastal afforestation that constitutes about 94.4 % of the growing stock. *Sonneratia caseolaris* is another prominent tree species suitable for coastal plantation (Mahmood, 2015; Mahmood et al., 2020a). Recently, promoting carbon sequestration as climate-change mitigation measures has added as new objectives of coastal afforestation in Bangladesh (Mahmood et al., 2020). Biomass estimation in mangroves is prerequisite to estimate the carbon stocking/sequestration, which ultimately ensure the sustainable utilization of forest resources (Petersson et al., 2012; Mahmood, 2014; Rahman et al., 2021).

Biomass of an individual tree or a forest can be estimated accurately by different approved methods like- whole tree method, allometric equations etc. In spite of higher accuracy, the whole tree method is discouraged due to its time and labor-consuming sampling process and destructive nature. The allometric model is widely accepted in semi-destructive and non-destructive ways for its accuracy and less vicious features with easily measurable variables (Picard et al., 2012; Sileshi, 2014). *Sonneratia apetala* has biomass models for the Sundarbans (Mahmood et al., 2019), but no such study has been done on *S. caseolaris*. Accurate estimation of carbon stock in the coastal afforested areas requires assessing the carbon stock in five pools of a mangrove ecosystem (Mahmood 2014). Environmental conditions, species composition and management practices significantly influence the carbon stock in mangroves. However, age is generally an important driving factor in the carbon dynamics of mangrove ecosystems (Harishma et al., 2020). This study aimed to i) develop site and species-specific biomass model for *S. apetala* and *S. caseolaris* b) estimate the TAGB and belowground biomass and carbon stock in young and mature planted sites in the coastal areas of Bangladesh.

Methodology

Study area

The study sites were located between (22.0458°N–89.9689°E) of the central coastal areas of Bangladesh on the bank of the Bishkhali River at Barguna district (Fig. 1). These sites enjoy a tropical monsoon climate

with 2588 mm average annual rainfall. Yearly average temperature and wind speed ranges from 33.3 °C to 12.1 °C, and 2.2 to 2.9 knots (DSE and MoE 2015).

The study site is an accreted land formed on the western bank of the Bishkhali River, features a nearly flat to the gentle slope (0.5 –1.0 %), regular inundation during high tide, direct wave action, flow and turbulence of the river current. Soil texture is silt loam to silty clay loam. Site-1 constitutes a young mangrove plantation (<20 years) with *S. apetala* and *S. caseolaris* with average 150 m width belt plantation. Site-2 constitutes a comparatively older plantation (>40 years) with *S. apetala*.

Allometric model development for *Sonneratia apetala* and *Sonneratia caseolaris*

Fifty sample trees (Data set A) for each species were selected purposively, and the semi-destructive method (Picard et al., 2012) was adopted to estimate biomass. Sectional diameter (cm) at 3 m intervals for the prominent/bigger branches (diameter > 7 cm) and stem, and total height (TH, cm) of these trees were measured. The base diameter of all smaller/non-prominent branches (diameter < 7 cm) was also measured. Thirty smaller branches of each species were trimmed in the field. Leaves (L), leaf-containing branches (LCB) and woody branches (WBs) of the trimmed branched were separated, and their fresh biomass was measured. Ten fresh sub-samples (≥ 250 g) of each part (leaf, branch, stem with bark, stem without bark and bark) of both species were collected and oven-dried (80 °C for seven days) to a constant weight for deriving a fresh weight to oven-dry weight conversion factor for fresh to oven-dry weight (Mahmood et al., 2019). The biomass of bigger branches and stems was calculated from each species' D, H, volume (m^3) and wood density. Species-specific wood density (W) values of the studied species were taken from Satter et al. (1999).

Best-fit models for the different plant parts were developed from 20 linear regression models. Here, DBH and H were used as independent variables. At the same time, the biomass of leaf, branch, stem, bark, and total aboveground biomass were considered dependent variables (Table 1). SAS statistical software (University Edition) was used to test

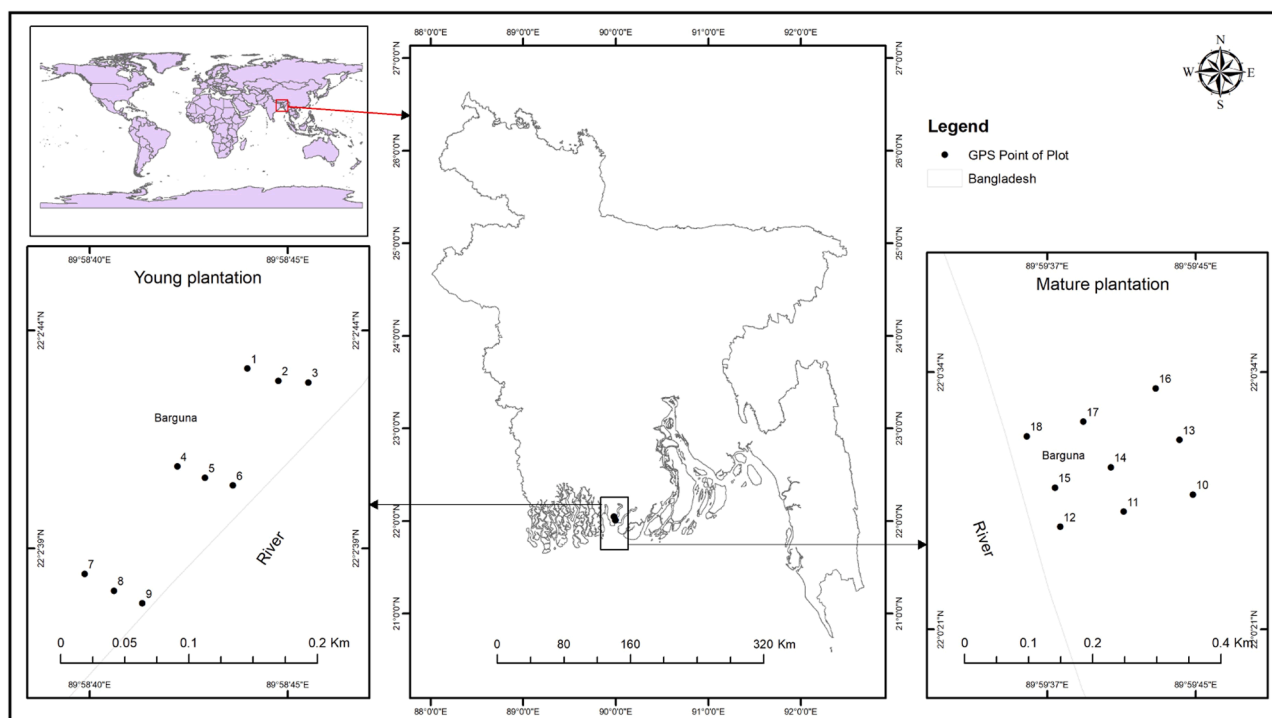


Fig. 1. Study area including young plantation and mature plantation site.

the level of significance of the derived equations. A correction factor (CF) was calculated for each equation to minimize systematic bias when converting back to biomass values from the Ln transformation (Sprugel, 1983). The equation with the highest R^2 , and the lowest value of RMSE, ESS, SEE, a, b, c, AICc, CF and Furnival Index was considered the best fit (Sileshi, 2014).

Model evaluation

Model evaluation is the next step of model development, which can

$$\text{TAGB (t/ha)} = \text{Live tree biomass (t/ha)} + \text{Leaf litter biomass (t/ha)} + \text{Fine woody debris biomass (t/ha)} \quad (1)$$

be achieved through testing the Root Mean Square Error (RMSE) and Model Efficiency (ME) of the respective models. In this study, these two parameters had been observed in derived model and other widely used model for the two sites (Mayer and Butler, 1993) (Table 2). Twenty-five individuals (Data Set B) for both the *S. apetala* and *S. caseolaris* from the corresponding sites were selected to evaluate the models. The relation between predicted and observed biomass was examined for the derived models and other frequently used models.

Above ground biomass and carbon stock assessment

Sampling design

Three (3) transects (perpendicular to shoreline) had been assigned in both Site I and Site II. Each transect contained three sample plots (10 m

$$\text{Carbon in TAGB (t/ha)} = \text{Carbon in live tree biomass (t/ha)} + \text{Carbon in leaf litter (t/ha)} + \text{Carbon in fine woody debris (t/ha)} \quad (2)$$

x 10 m) that were located at the shoreward end, middle part and landward of the plantation (Fig. 2a). Four nested plots (1 m x 1 m) were demarcated at four corners of each sample plot (Fig. 2b).

Table 1
Allometric models of *Sonneratia apetala* and *Sonneratia caseolaris*.

Regression Equations	
$\text{LnY} = a + b\text{LnD} + c\text{LnH}$	$\text{LnY} = a + b\text{LnH}$
$\text{LnY} = a + bD + cH$	$\text{LnY} = a + bH$
$\text{LnY} = a + b\text{LnD}$	$Y = a + bD^{2H}$
$\text{LnY} = a + bD$	$Y = a + bDH$
$Y = a + bD + cH$	$Y = a + bH$
$\text{LnY} = a + b\text{LnD}^{2H}$	$Y = a + b\text{LnD} + c\text{LnH}$
$\text{LnY} = a + b\text{LnDH}$	$Y = a + b\text{LnD}$
$\text{LnY} = a + bDH$	$Y = a + b\text{LnD}^{2H}$
$Y = a + bD$	$Y = a + b\text{LnDH}$
$\text{LnY} = a + bD^{2H}$	$Y = a + b\text{LnH}$

Table 2
Allometric models for validation and comparison.

Models
Mahmood et al., 2019 (<i>Sonneratia apetala</i> for the natural mangrove, Sundarbans)
Mahmood et al., 2019 (Common allometric model for the Sundarbans)
Komiyama et al. (2005)
Chave et al. (2014)
Njana et al. (2016)

Measurements and sample processing

Each individual within the sample plots was recorded with its height and DBH. Leaf litter and fine wood debris (<8 cm) were collected from the nested plots of each sample plot and were washed separately with care to remove soil from the leaves and oven-dried (80 °C for seven days). The dried samples were grounded, sieved and stored in airtight container for further analysis (Allen, 1989). Similarly, the dried sub-samples of leaves, smaller branches, bigger branches, stems, and barks of *S. apetala* and *S. caseolaris* were grounded, sieved through 2 mm mesh and stored in airtight containers for further analysis.

Calculation of above ground biomass and carbon stock

The total above-ground biomass (TAGB) of individual tree estimated using the derived allometric models of this study. The TAGB of site 1 and 2 were estimated at plot level and expressed in t/ha a. The oven-dry weight of leaf litter and fine woody debris were measured, recorded and expressed in t/ha for both site 1 and site 2. Eq. (1) was used to estimate the TAGB for site 1 and 2.

The organic carbon concentration in plant and litter samples were measured according to Allen (1989). Finally, carbon concentration of each component was multiplied with biomass to get the carbon stock of the respective component. Carbon stock in the TAGB was estimated using Eq. (2).

Belowground biomass and carbon stock assessment

Sampling design, sampling of root and sample processing

Soil pit (1 m x 1 m x 1 m) method was adopted to estimate the root biomass of mangroves (Komiyama et al., 2005). Out of three sample plots of each transect, one sample plot was plot was purposively chosen to excavate one pit for the collection of coarse roots (>2 cm) and fine roots (≤2 cm) as suggested by Meng et al. (2018). Three pits from each site were excavated in a pattern that one was located at shoreline, second was at the middle position of the stand and third was at the landward. The soil of each pit was excavated and washed in the field using a water jet and sieved through a 2 mm mesh. The roots of each pit were sorted into coarse (>2 cm) and fine root (<2 cm), weighted in the field and recorded separately for sites 1 and 2. Sub-samples (250 g) of coarse and fine roots from both sites were oven-dried (80 °C for seven days) for a conversion factor to calculate the dry weight. These subsamples were grounded, sieved through 2 mm mesh and stored in an airtight container for further analysis.

Root biomass and carbon stock

Coarse and fine root biomass for each site were estimated using their fresh biomass that measured in the field and their corresponding conversion factors for dry weight. Finally, oven dry biomass of coarse and fine roots was recorded separately according to sites and expressed in t/ha using Eq. (3). Carbon concentration in coarse and fine roots were

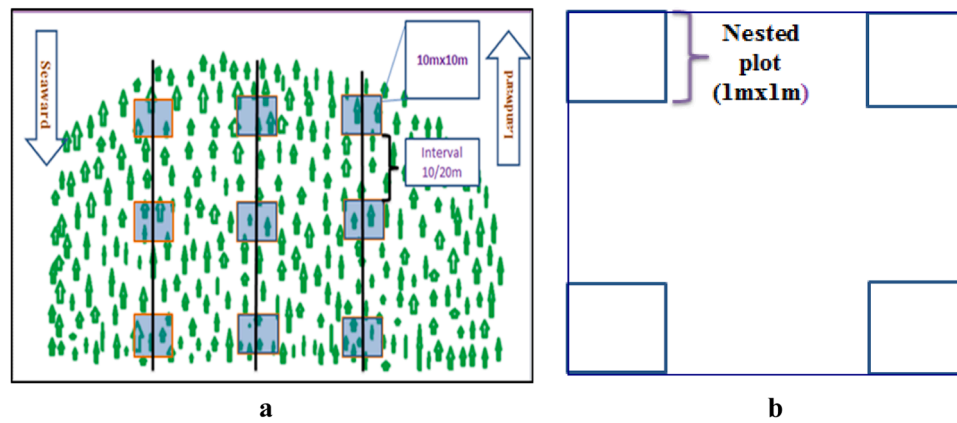


Fig. 2. Layout of the sample plots.

measured according to Allen (1989) and the carbon stock in root biomass was calculated using Eq. (4).

Soil bulk density and carbon concentration

Open face soil auger (5 cm diameter) was deployed to collect soil samples up to 1 m depth. Soil samples for the bulk density were collected

$$\text{Root biomass (t/ha)} = \text{Coarse root biomass (t/ha)} + \text{Fine root biomass (t/ha)} \quad (3)$$

$$\text{Carbon in root biomass (t/ha)} = \text{Carbon in coarse root biomass (t/ha)} + \text{Carbon in fine root biomass (t/ha)} \quad (4)$$

Table 3

Allometric models for *Sonneratia apetala* of coastal plantation. Equation with '*' mark indicates best fit allometric models.

Plant parts	a	b	c	Adjusted R ²	ESS (Residual SS)	AICc	SEE (model SE)	Correction Factor	RMSE	Furnival index
Equation for Leaf										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-1.92	1.96	-0.93	0.84	8.82	-145.66	0.36	1.07	0.13	1.3
$\text{LnY} = a + bD + cH$	-0.01	0.11	-0.06	0.79	11.74	-124.83	0.41	1.09	0.17	1.5
$\text{LnY} = a + b\text{LnD}$	-2.21	1.27		0.78	12.25	-123.94	0.42	1.09	0.17	1.53
$\text{LnY} = a + bD$	-0.19	0.08		0.76	13.46	-117.1	0.44	1.1	0.19	1.6
$Y = a + bD + cH$	-0.16	0.63		0.84	202.02	82.89	1.7		2.89	1.7
Equation for Branch										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-1.69	2.43	-0.86	0.88	12.28	-121.52	0.42	1.09	0.18	3.53
$\text{LnY} = a + b\text{LnD}$	-1.96	1.79		0.85	15.23	-108.04	0.46	1.11	0.21	3.9
$\text{LnY} = a + bD + cH$	1.03	0.13	-0.04	0.83	17.54	-95.49	0.5	1.13	0.25	4.21
$\text{LnY} = a + bD$	0.9	0.11		0.82	18.47	-93.99	0.51	1.14	0.26	4.29
$\text{LnY} = a + b\text{LnD}^2H$	-1.96	0.62		0.79	21.23	-83.8	0.55	1.16	0.3	4.6
Equation for Stem without Bark										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-3.6	2.11	0.72	0.99	2.11	-250.13	0.17	1.02	0.03	2.48
$\text{LnY} = a + b\text{LnD}^2H$	-3.64	0.96		0.99	2.34	-244.77	0.18	1.02	0.03	2.6
$\text{LnY} = a + b\text{LnD}$	-3.37	2.65		0.98	4.2	-202.01	0.24	1.03	0.06	3.48
$\text{LnY} = a + b\text{LnDH}$	-3.68	1.48		0.98	4.53	-196.51	0.25	1.03	0.06	3.61
$Y = a + bD^2H$	5.75	0.02		0.97	42,785.87	471.61	24.55		602.62	24.55
Equation for Stem with Bark										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-3.25	2.02	0.73	0.99	2.06	-251.8	0.17	1.01	0.03	2.45
$\text{LnY} = a + b\text{LnD}^2H$	-3.29	0.93		0.99	2.22	-248.61	0.18	1.02	0.03	2.53
$\text{LnY} = a + b\text{LnDH}$	-3.32	1.44		0.98	4.14	-203.18	0.24	1.03	0.06	3.45
$\text{LnY} = a + b\text{LnD}$	-3.02	2.57		0.98	4.22	-201.82	0.24	1.03	0.06	3.48
$Y = a + bD^2H$	8.2	0.02		0.97	51,001.81	484.44	26.8		718.34	26.8
Equation for Bark										
$\text{LnY} = a + b\text{LnD}^2H^*$	-3.79	0.7		0.98	2.07	-253.88	0.17	1.01	0.03	0.78
$\text{LnY} = a + b\text{LnD} + c\text{LnH}$	-3.79	1.38	0.73	0.98	2.06	-251.8	0.17	1.01	0.03	0.78
$\text{LnY} = a + b\text{LnDH}$	-3.83	1.08		0.98	2.58	-237.73	0.19	1.02	0.04	0.87
$\text{LnY} = a + b\text{LnD}$	-3.56	1.92		0.96	4.22	-201.82	0.24	1.03	0.06	1.11
$Y = a + bDH$	-0.7	0.04		0.97	165.63	66.16	1.53		2.33	1.53
Equation for TAGB										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-1.89	2.1	0.23	0.98	2.95	-225.75	0.21	1.02	0.04	3.6
$\text{LnY} = a + b\text{LnD}$	-1.82	2.28		0.98	3.15	-223	0.21	1.02	0.04	3.7
$\text{LnY} = a + b\text{LnD}^2H$	-1.99	0.82		0.97	4.36	-199.34	0.25	1.03	0.06	4.35
$\text{LnY} = a + b\text{LnDH}$	-1.99	1.26		0.95	7.36	-161.11	0.32	1.05	0.1	5.66
$\text{LnY} = a + bD + cH$	1.66	0.1	0.07	0.92	11.41	-126.92	0.4	1.08	0.16	7.09

from the center of each plot at a depth of 0–15 cm, 15–30 cm, 30–50 cm and 50–100 cm. Nine samples for each layer were collected from each site. Collected samples were oven-dried (105 °C until constant weight), measured, and recorded. These samples were crushed, sieved and stored in airtight containers separately for future analysis. Eq. (5) was used to estimate the bulk density of the collected soil sample. Organic carbon concentration in soil samples were measured according to Allen (1989). Carbon stock in soils up to 1 m depth of both the sites was estimated from bulk density values and carbon concentration of the respective depth.

$$\text{Bulk density (g cm}^{-3}\text{)} : \text{Dry weight (g)} / \text{Sample volume (cm}^3\text{)} \quad (5)$$

Results

Allometric model for *Sonneratia apetala*

In this study, DBH and TH are considered as independent variables and 20 linear regression equations were tested using the DBH and TH combinations for each plant parts and TAGB for both the *S. apetala* and *S. caseolaris*. In spite of having significance level ($p < 0.05$) majority regression equations had to be discarded considering the coefficient of determination (R^2) value < 0.75 for leaves, 0.79 for branches, 0.95 for stem without bark, stem with bark and bark; 0.90 for total aboveground biomass of the *S. apetala*. Among the selected equations, the best-fit model for each part was chosen considering a set of parameters such as the highest R^2 , with the lowest value of AICc, CF, ESS, Furnival Index and RMSE (Furnival, 1961; Soares et al., 2005; Sileshi, 2014; Mahmood et al., 2016). The selected allometric models were Ln Biomass = $-1.9173 + 1.9566 \text{ LnD} + 0.8417 \text{ LnH}$; Ln Biomass = $-1.6902 + 2.4272 \text{ LnD} - 0.8588 \text{ LnH}$; Ln Biomass = $-3.6008 + 2.1139 \text{ LnD} + 0.7236 \text{ LnH}$; Ln Biomass = $-3.2523 + 2.0201 \text{ LnD} + 0.7337 \text{ LnH}$; Ln Biomass = $-3.7887 + 0.7007 \text{ LnD}^2 + 2.1048 \text{ LnD} + 0.2282 \text{ LnH}$ for leaves, branches, stems without bark, stems with bark, bark and TAGB, respectively of *S. apetala* (Table 3).

Model valuation for *Sonneratia apetala*

We had calculated the value of model prediction error (MPE) and residual mean square error (RMSE) for the best-fit and other widely used models. For the best-fit TAGB model, the RMSE (12.30 %) and MPE (14.67 %) values were lower compared to other models including the previous allometric model of *S. apetala* (Mahmood et al., 2019). The percentage of RMSE and MPE of the previous allometric model of *S. apetala* and common allometric model for the Sundarbans were quite closer but ranked the 2nd and 3rd lowest respectively (Table 4). The graphical demonstration of 1:1 line for the best-fit TAGB model showed higher accuracy in biomass estimation of *S. apetala* than other widely used models (Fig. 3).

Table 4
Model comparison and validation for *S. apetala*.

Models	MPE (%)	ME	RMSE (%)
This study (Best fit TAGB model of <i>Sonneratia apetala</i>)	14.67	0.98	12.30
Mahmood et al., 2019 (<i>Sonneratia apetala</i> for the Sundarbans)	19.06	0.98	14.25
Mahmood et al., 2019 (Common allometric model for the Sundarbans)	19.72	0.96	17.98
Komiyama et al. (2005)	46.56	0.58	61.80
Chave et al. (2014)	26.25	0.89	31.66
Njana et al. (2016)	62.09	0.66	55.64

Allometric model for *Sonneratia caseolaris*

A good numbers of regression equations were discarded considering the coefficient of determination (R^2) value < 0.85 for leaves, 0.87 for branches, 0.99 for stems without bark and stems with bark, 0.97 for barks; R^2 value < 0.97 for TAGB. The selected allometric models were Ln Biomass = $-5.0571 + 2.8495 \text{ LnD} - 0.8979 \text{ LnH}$; Ln Biomass = $-4.5829 + 3.5769 \text{ LnD} - 1.0012 \text{ LnH}$; Ln Biomass = $-3.7841 + 2.0914 \text{ LnD} + 0.6809 \text{ LnH}$; Ln Biomass = $-3.4328 + 2.0190 \text{ LnD} + 0.6659 \text{ LnH}$; Ln Biomass = $-3.9906 + 0.6822 \text{ LnD}^2 + 2.3110 \text{ LnD} + 0.3476 \text{ LnH}$ for leaves, branches, stems without bark, stems with bark, barks and TAGB, respectively of *S. caseolaris* (Table 5).

Model evaluation for *Sonneratia caseolaris*

The best-fit TAGB model showed lower values of RMSE (10.91 %) and MPE (10.57 %) than other models including the common allometric model for the Sundarbans (Mahmood et al., 2019). The percentage of RMSE and MPE of the (Chave et al., 2014) ranked the 2nd lowest (Table 6). Similarly, in case of graphical demonstration of 1:1 line, the best-fit TAGB model of present study was performed higher accuracy in biomass estimation of *S. caseolaris* compared to other widely used models. The biomass model of Komiyama et al. (2005) and Njana et al. (2016) overvalued the total aboveground biomass (Fig. 4).

Aboveground biomass and carbon stock

We assessed total TAGB and carbon stock for both sites and these two parameters varied significant ($p < 0.05$) between sites. Comparatively higher biomass and carbon stock was detected for site 2 (older plantation) compared to site 1 (younger plantation). However, biomass and carbon stock in leaf, fine woody debris and leaf litter were not varied significant ($p > 0.05$) between the sites (Table 7).

Belowground biomass and carbon stock estimation

Comparatively higher root biomass and carbon stock were observed for site 2 (older plantation) compared to site 1 (younger plantation). However, biomass and carbon stock in fine roots were not varied significant ($p > 0.05$) between the sites (Table 8). Carbon stock in soil for the site 1 and site 2 were $272.80 \pm 21.89 \text{ t/ha}$ and $320.75 \pm 22.23 \text{ t/ha}$ respectively and it was not varied significantly ($p > 0.05$) between the sites.

Ecosystem carbon stock

The mean carbon stock (aboveground + belowground) of site 1 and site 2 were estimated to be $350.53 \pm 14.23 \text{ t C/ha}$ and $483.64 \pm 16.35 \text{ t C/ha}$, respectively and showed significant ($p < 0.05$) variations between the sites. The average estimated CO₂ equivalent of site 1 and site 2 were estimated to be approximately $1282.92 \pm 14.23 \text{ t CO}_2\text{/ha}$ and $1770.14 \pm 16.35 \text{ t CO}_2\text{/ha}$ respectively and showed significant ($p < 0.05$) variations between the sites (Fig. 5).

Discussion

Allometric biomass development and evaluation

Allometric models for biomass estimation is a mathematical method which can be developed from the correlations between different measurable parameters of a tree like DBH), height of the tree trunk (H), total height (TH), crown diameter, wood density etc. and the biomass of that particular tree. DBH and TH are the mostly used independent variables from ancient time to recent years (Komiyama et al., 2002; Cienfiala et al., 2006; Mahmood et al., 2019, 2021). Selection of appropriate

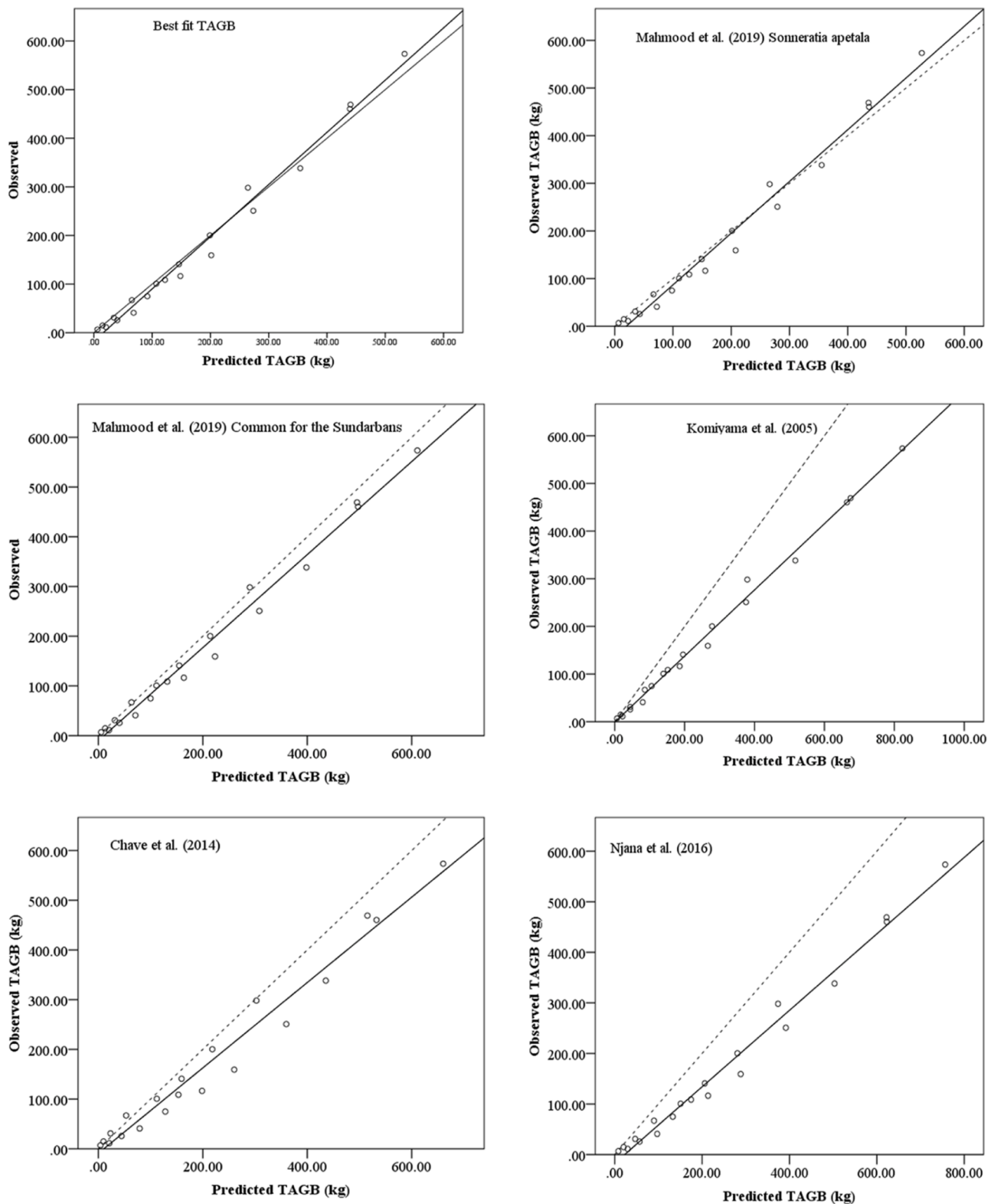


Fig. 3. Regression between observed and predicted values of the best fit common TAGB model of the *Sonneratia apetala* and frequently used regional and pan-tropical total above-ground biomass models. Solid line is the regression line and broken line is the significance of slope ($b = 1$) and intercept ($a = 0$).

allometric models requires accuracy in every stage like selection of biomass estimation method (Destructive, semi-destructive, non-destructive and mean tree method) and independent variables, selection and critical analysis of parameters, which are recognized and applied by several researchers (Soares et al., 2005; Sileshi, 2014; Mahmood et al.,

2016).

DBH and TH were considered as independent variables and 20 linear regression equations were tested using the DBH and TH combinations for each plant parts and TAGB for both the *S. apetala* and *S. caseolaris* (Table 1). Then best fit models for each component was selected

Table 5Allometric models for *Sonneratia caseolaris* of coastal plantation. Equation with '*' mark indicates best fit allometric models.

Plant parts	a	b	c	Adjusted R ²	ESS (Residual SS)	AICc	SEE (model SE)	Correction Factor	RMSE	Furnival index
Equation for Leaf										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-5.06	2.85	-0.90	0.91	8.52	-79.61	0.43	1.09	0.18	1.15
$\text{LnY} = a + b\text{LnD}$	-5.96	2.33		0.9	9.14	-78.44	0.44	1.1	0.19	1.18
$\text{LnY} = a + b\text{LnD}^2\text{H}$	-6.77	0.89		0.88	11.01	-69.12	0.48	1.12	0.23	1.29
$Y = a + bD^2H$	0.3	0		0.88	64.22	19.04	1.16		1.34	1.16
$\text{LnY} = a + b\text{LnDH}$	-7.2	1.43		0.86	12.81	-61.58	0.52	1.14	0.27	1.39
Equation for Branch										
$Y = a + bD^2H$	-5.03	0.01		0.92	9690.49	269.87	14.21		201.89	14.21
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-4.58	3.58	-1.00	0.92	12.34	-61.09	0.51	1.14	0.26	4.25
$\text{LnY} = a + b\text{LnD}$	-5.59	3		0.91	13.11	-60.41	0.52	1.15	0.27	4.34
$\text{LnY} = a + b\text{LnD}^2\text{H}$	-6.63	1.15		0.89	15.94	-50.64	0.58	1.18	0.33	4.79
$\text{LnY} = a + b\text{LnDH}$	-7.2	1.85		0.88	18.74	-42.55	0.62	1.22	0.39	5.19
Equation for Stem without bark										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-3.78	2.09	0.68	0.99	0.48	-223.31	0.1	1.01	0.01	1.42
$\text{LnY} = a + b\text{LnD}^2\text{H}$	-4.05	0.96		0.99	0.54	-219.65	0.11	1.01	0.01	1.49
$\text{LnY} = a + b\text{LnD}$	-3.1	2.48		0.99	0.84	-197.8	0.13	1.01	0.02	1.85
$\text{LnY} = a + b\text{LnDH}$	-4.59	1.56		0.99	1.09	-184.83	0.15	1.01	0.02	2.11
$Y = a + bD^2H$	2.83	0.01		0.99	5747	243.74	10.94		119.73	10.94
Equation for Stem with Bark										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-3.43	2.02	0.67	0.99	0.46	-225.77	0.1	1	0.01	1.46
$\text{LnY} = a + b\text{LnD}^2\text{H}$	-3.69	0.93		0.99	0.51	-222.5	0.1	1.01	0.01	1.53
$\text{LnY} = a + b\text{LnD}$	-2.76	2.4		0.99	0.8	-200.16	0.13	1.01	0.02	1.91
$\text{LnY} = a + b\text{LnDH}$	-4.21	1.51		0.99	1.02	-188.23	0.15	1.01	0.02	2.15
$Y = a + bD^2H$	4.8	0.01		0.99	6552.85	250.3	11.68		136.52	11.68
Equation for bark										
$\text{LnY} = a + b\text{LnD}^2\text{H}^*$	-3.99	0.68		0.99	0.46	-228.12	0.1	1	0.01	0.44
$\text{LnY} = a + b\text{LnD} + c\text{LnH}$	-3.98	1.37	0.67	0.99	0.46	-225.77	0.1	1	0.01	0.45
$\text{LnY} = a + b\text{LnDH}$	-4.38	1.11		0.99	0.61	-213.71	0.11	1.01	0.01	0.51
$\text{LnY} = a + b\text{LnD}$	-3.3	1.76		0.98	0.8	-200.16	0.13	1.01	0.02	0.59
$Y = a + bDH$	-0.58	0.03		0.97	38.58	-6.44	0.9		0.8	0.9
Equation for Total Above-ground biomass										
$\text{LnY} = a + b\text{LnD} + c\text{LnH}^*$	-3.09	2.31	0.35	0.99	0.91	-191.24	0.14	1.01	0.02	2.43
$\text{LnY} = a + b\text{LnD}$	-2.74	2.51		0.99	1.01	-188.73	0.14	1.01	0.02	2.52
$\text{LnY} = a + b\text{LnD}^2\text{H}$	-3.68	0.97		0.99	1.22	-179.31	0.16	1.01	0.03	2.77
$Y = a + bD^2H$	0.07	0.02		0.98	17,761.27	300.16	19.24		370.03	19.24
$\text{LnY} = a + b\text{LnDH}$	-4.21	1.57		0.98	2.09	-152.2	0.21	1.02	0.04	3.64

Table 6Model comparison and validation for *S. caseolaris*.

Models	MPE (%)	ME	RMSE (%)
This study (Best fit TAGB model of <i>Sonneratia caseolaris</i>)	10.57	0.99	10.91
Mahmood et al., 2019 (Common allometric model for the Sundarbans)	28.50	0.96	19.70
Komiyama et al. (2005)	45.04	0.77	47.04
Chave et al. (2014)	19.50	0.95	20.82
Njana et al. (2016)	116.90	-0.13	103.81

considering a set of parameters. Though species specific allometric model for the *S. apetala* was developed previously for the natural mangroves (The Sundarbans) (Mahmood et al., 2019), but present study was conducted for the planted sites. Only development of allometric model for biomass estimation is not sufficient, justification of variation and applicability of derived model are also required for accurate biomass estimation. To satisfy this issue present study had made a comparison among the developed model and other widely recognized and applied models (Table 2). In case of both species, the biomass estimated from other widely used models was either overestimated or underestimated compared to developed models (Fig. 3,4) and this scenario was also observed in previous studies for different species (Ngomanda et al., 2014; Mahmood et al., 2020b). Such deviations can be detected because the total biomass accumulation in different parts of the tree and finally the total biomass depends mainly on the species, age, geographical and environmental factors of the habitat (Mahmood et al., 2004; Mugasha et al., 2016). The current study suggested using the site and

species-specific allometric models for the biomass estimation of planted individuals of both *S. apetala* and *S. caseolaris* in the coastal plantation site of Bangladesh.

Biomass and carbon stock

The estimated TAGB of the mature plantation was 318.55 ± 17.71 t/ha, which was 1.95 times higher than the young plantations (163.56 ± 10.67 t/ha). While, carbon stock in TAGB was 2.1 times greater than young plantations. Here the environment factors are same for the both sites, so the tree age can a driver for the variation in biomass and carbon buildup capacity (Kohl et al., 2017). The AGB and AGC in plantation were 125.5 ± 22.6 t/ha and 90.6 ± 16.2 t/ha, respectively in Mahanadi Mangroves of India (Sahu et al., 2016) which is quite similar with current study.

Present study assessed both the root and soil biomass to evaluate the total belowground carbon stock. In case of both fine root and coarse root, biomass and carbon stock were observed higher in site 1 than site 2 (Table 8). Ahmed et al. (2022) found the mean below-ground roots carbon (BGRC) of the plantation was 11.8 ± 1.4 t/ha, which is also similar with the current study. For the aboveground biomass study, allometric biomass models have been established for the both studied species. But the allometric models for root biomass calculation have not established yet for the *S. apetala* and *S. caseolaris*. Though Komiyama et al. (2005) established the common models for mangrove root biomass calculation but site and species-specific models are compulsory for correct biomass quantification because the mangrove root structure and morphological adaptations related to roots varies with species and site quality (Dupuy et al., 2005; Duke, 2011). In present study, the total

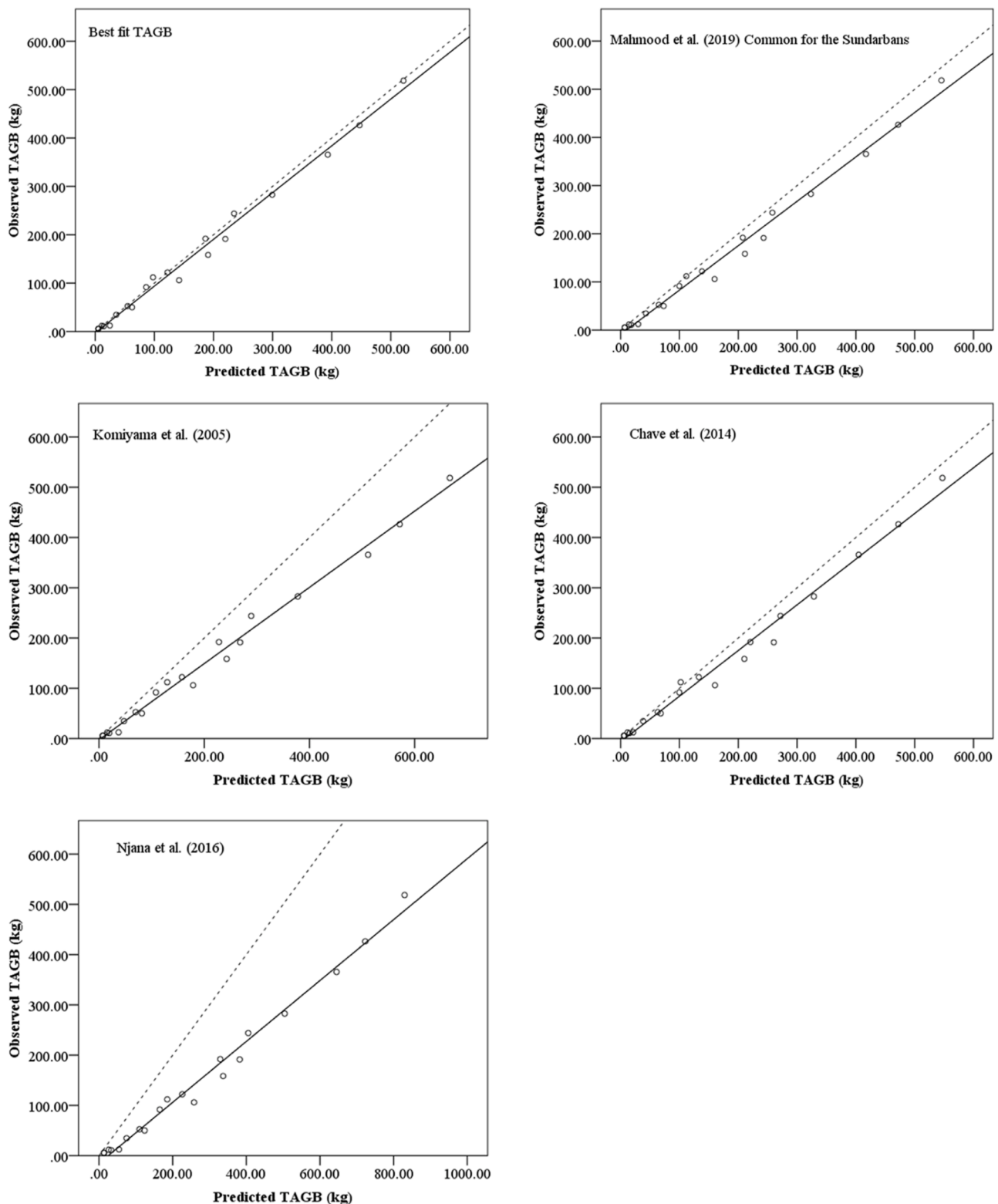


Fig. 4. Regression between observed and predicted values of the best fit common TAGB model of the *Sonneratia caseolaria* and frequently used regional and pan-tropical total above-ground biomass models. Solid line is the regression line and broken line is the significance of slope ($b = 1$) and intercept ($a = 0$).

below ground carbon stocks in the mature plantation is 1.18 times higher than young plantation and the range appears higher than the values (63.87 ± 8.67 t/ha) reported by Sahu et al. (2016) and Vinod et al. (2018) for Mahanadi mangroves and Kadalundi mangroves respectively.

An ecosystem carbon stock is the combination of above and

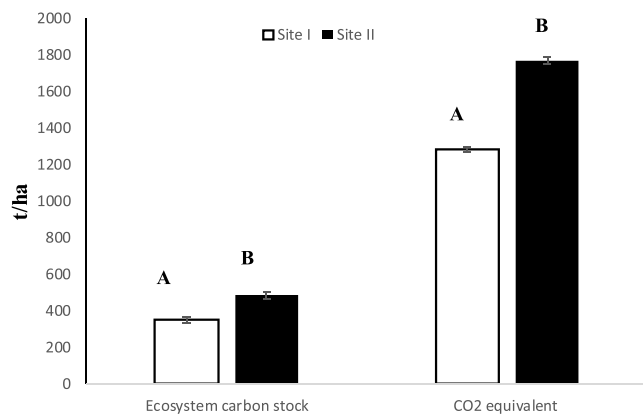
belowground carbon stock (Houghton, 2007). Several issues such as tree/forest age, density, species composition, forest management practices, climatic and edaphic conditions etc. act as factors for the carbon distribution in different tree components of mangroves (Jahnke, 2005; Prasad and Ramanathan, 2009; Alongi and Mukhopadhyay, 2015; Phillips et al., 2017). In current study, the mean ecosystem carbon stock

Table 7Above ground biomass and carbon stock. ** indicates significant ($p < 0.05$) differences between two sites for the same studied component.

Component		Biomass (t/ha)		Carbon stock (t/ha)	
		Site 1	Site 2	Site 1	Site 2
(i) Tree	Leaf	3.54±0.26	4.21±0.28	1.55±0.12	1.88±0.13
	Branch	20.75±1.11*	35.34±2.52*	10.05±0.55*	17.60±1.14*
	Bark	11.99±0.81*	15.60±0.78*	4.62±0.39*	7.05±0.36*
	Stem without bark	127.27±8.49*	263.39±14.13*	55.96±5.46*	124.86±8.84*
(ii) Fine wood debris		0.0053±0.00088	0.0060±0.00079	0.0027±0.00041	0.0027±0.00037
(iii) Leaf litter		0.0069±0.00128	0.0021±0.00018	0.0028±0.00068	0.0008±0.000081
Total AGB (i+ii+iii)		163.56±10.67*	318.55±17.71*	72.19±6.57*	151.39±10.47*

Table 8Below ground biomass and carbon stock. ** indicates significant ($p < 0.05$) differences between two sites for the same studied component.

Component		Biomass (t/ha)		Carbon stock (t/ha)	
		Site 1	Site 2	Site 1	Site 2
Root	Coarse	2.98±0.31*	16.32±2.87*	1.31±0.13*	7.76±1.36*
	Fine	11.55±1.36	9.34±3.13	4.23±0.49	3.74±1.25

**Fig. 5.** Ecosystem carbon-stocks and CO₂ equivalent potential of the study area.

of site 1 and site 2 were estimated 350.53 ± 14.23 t C/ha and 483.64 ± 16.35 t C/ha, respectively (Fig. 5) and that is quite similar to the carbon stock of the natural and planted mangroves in Southeast Asia (332–2205 t C/ha) (Alongi 2012). According to Uddin et al. (2023), the mean ecosystem carbon stock of 25.5 years old mangrove plantations was 190.1 (± 30.3) ton/ha, which is relatively lower than the present study. This variation may be related to the variabilities of the species and the quality of these sites (Phillips et al., 2017). The distribution of carbon stock in the present study was 26 % and 72 % for the above-ground and soil, respectively. In mangroves, a larger portion of carbon is stored in soil than the TAGB (Alongi, 2009; Scharlemann et al., 2014; Chen et al., 2017). The average estimated CO₂ equivalents of site 1 and site 2 were calculated to be approximately 1282.92 t CO₂/ha and 1770.13521 t CO₂/ha, respectively (Fig. 5). If we can convert the vast portion of CO₂ into the economic return, then it would be around 220 US dollar/ ton of CO₂ which may be an indication that depicts the urge of conservation of mangroves as well as all-natural and planted tree coverage of the world (Kauffman et al., 2014; Moore and Diaz, 2015). Thus, by conserving the existing mangroves and creating a new range in degraded areas, we can balance the total carbon emission, which will help meet the IPCC goals for combating climate change impacts.

Conclusion

This study recommended assessing the biomass of *S. apetala* and *S. caseolaris* using the site and species-specific allometric models for the correct carbon accounting. The resulting allometric biomass models are

proficient in assessing the total above-ground biomass (TAGB) at a higher accuracy than the widely used biomass models for both species. Conversely, the accurate carbon assessment will contribute to mangrove valuation, which may promote preserving prevailing mangroves and renovating degraded areas.

Declaration of Competing Interest

There are no conflict of interest

Data availability

Data will be made available on request.

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