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Ecosystem carbon stock variation along forest stand ages: insight from eastern coast mangrove ecosystem of India

Muktipada Panda^{1,2}, Bikash R. Dash³ and Sudam C. Sahu^{1*}

Abstract

Background The mangrove ecosystem has the highest carbon sink potential which significantly contributes to bringing carbon neutrality. Understanding the carbon stock dynamics along the age of forest stands in the mangrove forest ecosystem is of significance for managing the forests and their carbon accumulation. This study aimed to estimate the forest structural attributes, biomass and total ecosystem carbon stock (TECS) of old natural (age > 50 years) and young planted (age ~ 20 years) mangrove forest stands at Bichitrapur Mangrove Reserve Forest in eastern coast of India. We also attempted to understand the interrelationship of structural attributes, biomass and soil properties in the mangrove forests. To achieve the results, twenty random plots were established (size: 20 m × 25 m) and suitable allometric equations along with species-specific wood density values were used to estimate the biomass and carbon stock.

Results Altogether, 29 plant species (18 exclusive and 11 associate species) were recorded. The mean total biomass ($\pm$ SE) and soil organic carbon (at 30 cm depth) were 165.31 ± 20.89 t ha⁻¹ and 40.20 ± 1.24 t C ha⁻¹ for young stands, and 586.12 ± 56.74 t ha⁻¹ and 49.68 ± 2.39 t C ha⁻¹ for old stands, respectively. Among mangrove species, *Avicennia marina* contributed the highest vegetation biomass in both forest stands (59.72 t ha⁻¹ and 262.28 t ha⁻¹ in young and old stands, respectively), followed by *Avicennia officinalis* (35.05 t ha⁻¹) and *Sonneratia apetala* (26.09 t ha⁻¹) in young stand and *Avicennia alba* (169.28 t ha⁻¹) and *Avicennia officinalis* (115.58 t ha⁻¹) in old stand. The mean TECS was 235.62 ± 27.34 t C ha⁻¹. The contribution of vegetation and soil to TECS was 63% and 37% in the young stand, whereas in the old stand it was 83% and 17%, respectively. The correlation analyses revealed that mean stand height ($r=0.87$), basal area ($r=0.99$), soil nitrogen ($r=0.76$), potassium ($r=0.78$), and carbon ($r=0.80$) were significantly positively correlated with total biomass at $p < 0.01$.

Conclusions Our results demonstrate that old mangrove forest stands store substantially high carbon stock than young planted forest stands, implying the role of forest age in determining the carbon storage potential of mangrove ecosystems.

Keywords Mangrove, Biomass, Importance value index, Total ecosystem carbon stock, Pearson's correlation

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Introduction

Mangroves and two other coastal ecosystems, i.e., seagrasses and salt marshes, are designated as 'blue carbon' ecosystems for their high potential and long-term natural carbon sinks (Lovelock and Duarte 2019). Their conservation and restoration have significantly contributed to offsetting atmospheric greenhouse gas (GHG) emissions and helped in adapting to climate change (Kathiresan et al. 2013; Alongi 2023). The annual primary production of global mangrove is 218 trillion grams of carbon (Kathiresan et al. 2013). They have the highest mean total ecosystem carbon stock (TECS) or 'C' stored together in biomass and soil (956 t C ha^{-1}) compared to salt marshes (593 t C ha^{-1}), peat swamps (408 t C ha^{-1}), rainforests (241 t C ha^{-1}), and sea grasses ($142.2 \text{ t C ha}^{-1}$) (Alongi 2014; Ouyang and Lee 2020). The TECS of the global mangrove ecosystem was estimated to be about 3.7–6.2 Pg (Ouyang and Lee 2020). Although mangroves have immense potential for climate change mitigation, deforestation and conversion to other land uses release greenhouse gases (GHG) which substantially contribute towards an increase in atmospheric temperature (Hamilton and Friess 2018). Despite their small global extent ($\sim 0.7\%$ of tropical forest area), deforestation of the mangrove ecosystem is responsible for 10% ($0.02\text{--}0.12 \text{ Pg C per year}$) of global CO_2 emissions (Donato et al. 2011; Siikamäki et al. 2012). Globally, the annual rate of mangrove loss is around $131\text{--}639 \text{ km}^2$ ($0.16\text{--}0.39\%$), which results in overall carbon loss of up to $2.0\text{--}7.5 \text{ Tg C yr}^{-1}$ (Hamilton and Casey 2016). Thus, conservation of mangrove carbon stocks has been promoted in global climate negotiations for their potential contribution in mitigating GHG emissions (Sasmito et al. 2020). Further, understanding the spatial distribution of blue carbon stocks of various mangrove ecosystems is vital to recognize their true potential for climate mitigation and also to strengthen conservation practices (Ragavan et al. 2021). The global aboveground biomass (AGB) and belowground biomass (BGB) of mangrove forests have been estimated at about 2.83 Pg and 1.11 Pg with a total biomass (TB) of 3.95 Pg (Hutchison et al. 2014). Somehow, the soil 'C' stocks are highly variable across countries and vary based on latitudes, geographical settings and plant community compositions. On average, mangrove soil contains $369 \pm 6.8 \text{ Mg C ha}^{-1}$. However, the value can range from $272 \pm 49 \text{ Mg C ha}^{-1}$ to $703 \pm 38 \text{ Mg C ha}^{-1}$ in the world's most carbon-poor and most carbon-rich mangroves in a one-meter depth of soil (Jardine and Siikamäki 2014). Thus, new plantations and regeneration of degraded mangrove areas will contribute to enhancing the global mangrove carbon stock to mitigate the global warming threat (Kathiresan et al. 2013).

Biomass carbon stock of mangrove forest is controlled by both biotic factors (i.e., species composition, growth forms, tree density, tree height, diameter of stem and age of stands) and abiotic factors (i.e., rainfall, temperature, river connectivity, salinity, cyclone frequency and intensity) (Rahman et al. 2015; Azad et al. 2019; Simard et al. 2019). The ecosystem 'C' stock increases with growth in the mangrove stand (Ragavan et al. 2021). In mangrove forest, stands with larger diameter at breast height (dbh), greater basal area, and higher canopy height hold more 'C' stock (Rahman et al. 2015). Young mangrove stands contain lower TECS than old undisturbed stands, whereas the carbon storage value increases with age and soil depth (Arif et al. 2017; Cadiz et al. 2020). The soil organic carbon (SOC) stock and burial rate were high in natural mangrove areas compared to restored areas (Gnanamoorthy et al. 2019). However, the soil carbon stock could vary based on mangrove tree density, sediment size and rate, and tide inundation (Cadiz et al. 2020). Very limited studies have investigated the interrelation between soil nutrients and stand structure of mangrove forests. The soil nutrients, especially essential macronutrients, influence the variation of mangrove AGB (Constance et al. 2022). The AGB significantly correlates with soil phosphorus ($r=0.85$, $p<0.01$), and salinity ($r=-0.79$, $p<0.05$) (Boto and Wellington 1984). In mangrove soil, the bulk density is an important parameter which negatively correlates with stand biomass and soil organic carbon (SOC) (Ball and Banerjee 2019). Thus, estimation of ecosystem carbon stock and elucidation of the relation between forest attributes, soil properties and carbon pool will help to understand the true carbon storage potential of the mangrove ecosystem and its sustainable conservation.

India's mangrove cover is $\sim 4992 \text{ km}^2$ ($\sim 2.7\%$ of global cover) (FSI 2021). The Indian East coast has the highest cover ($\sim 56.7\%$) followed by the West coast (23.5%) and the Andaman and Nicobar Islands (19.8%) (Kathiresan 2017). The biomass and carbon stock estimation of the Indian mangrove ecosystem has gained recent momentum, which has shown a range of variation across sites and forest stands within a mangrove ecosystem. The coastal stretch of Odisha state (on the east coast of India) is rich in mangrove coverage and taxonomic diversity. The suitable estuary habitats supported the growth of India's second-largest mangrove cover in Bhitarkanika National Park and other deltaic mangroves, which together cover about 250.64 km^2 of mangrove forest along the Odisha coast (FSI 2021). The major mangrove cover is found in the Mahanadi and Brahmani-Baitarani delta, between $86^\circ 48'$ and $86^\circ 58'$ E longitude and $20^\circ 40'\text{--}20^\circ 50'$ N latitude (Selvam 2003; Chellamani et al. 2014) and small extent ($<10 \text{ km}^2$) in river deltas of

Devi, and Subarnarekha. The mangrove forest of Subarnarekha delta, the Bichitrapur mangrove reserve forest (BMRF), was given little emphasis on their ecological significance and ignorance of their conservation and protection allowed their degradation to a large extent in the past (FSI 2021). This delta shares the border region with West Bengal and is nearest to the Sundarban (the world's largest mangrove ecosystem). The BMRF is an important mangrove ecosystem in terms of conservation of marine biodiversity, climate mitigation, coastal protection, etc. However, the entire mangrove ecosystem of BMRF has not been assessed at all for its floristic diversity, forest ecological attributes, carbon stock and soil characteristics. Considering all these limitations, we aimed (1) to estimate forest attributes (i.e., diversity, and structural attributes), biomass and carbon stock of old natural (age > 50 years) and young planted (age ~ 20 years) mangrove stands of BMRF, (2) to estimate species specific contribution of biomass 'C' stock in both forest stand ages and compare correlation of total biomass (TB) with stand structural attributes, and (3) to understand the interrelationship of diversity, structural attributes, biomass and soil properties as a whole for BMRF. We hypothesized that (1) old natural undisturbed mangrove forest stands store more blue 'C' than young planted

forest stands, and (2) the stand structural attributes and soil properties correlate with stand biomass.

Materials and methods

Description of study site

The BMRF is situated on the estuarine delta formed by alluvial deposits of the Subarnarekha river within the Bhograi revenue block of Balasore district, Odisha (India) (Fig. 1). The delta and nearby coastal stretch are geo-morphologically very dynamic, and very prone to natural hazards, i.e., frequent tropical cyclones, storm surges, strong tidal waves, and coastal flooding (Barman et al. 2016). Till the 1980s, the BMRF was left degraded by multiple drivers (i.e., development of human settlements, intensification of aquaculture, agriculture and natural calamities, etc.) and the remaining mangrove stands were part of the old natural mangrove forest (Roy and Datta 2018). After the huge devastation caused by the 1999 supercyclone on the Odisha coast, the importance of mangrove forest in coastal protection was highly recognized by the Government of Odisha and selective mangrove plantations were made along the entire Odisha coast, including the Subarnarekha river delta. The site experiences a typical tropical monsoon climate. The mean atmospheric temperature reaches the highest (40 °C) in April–May and

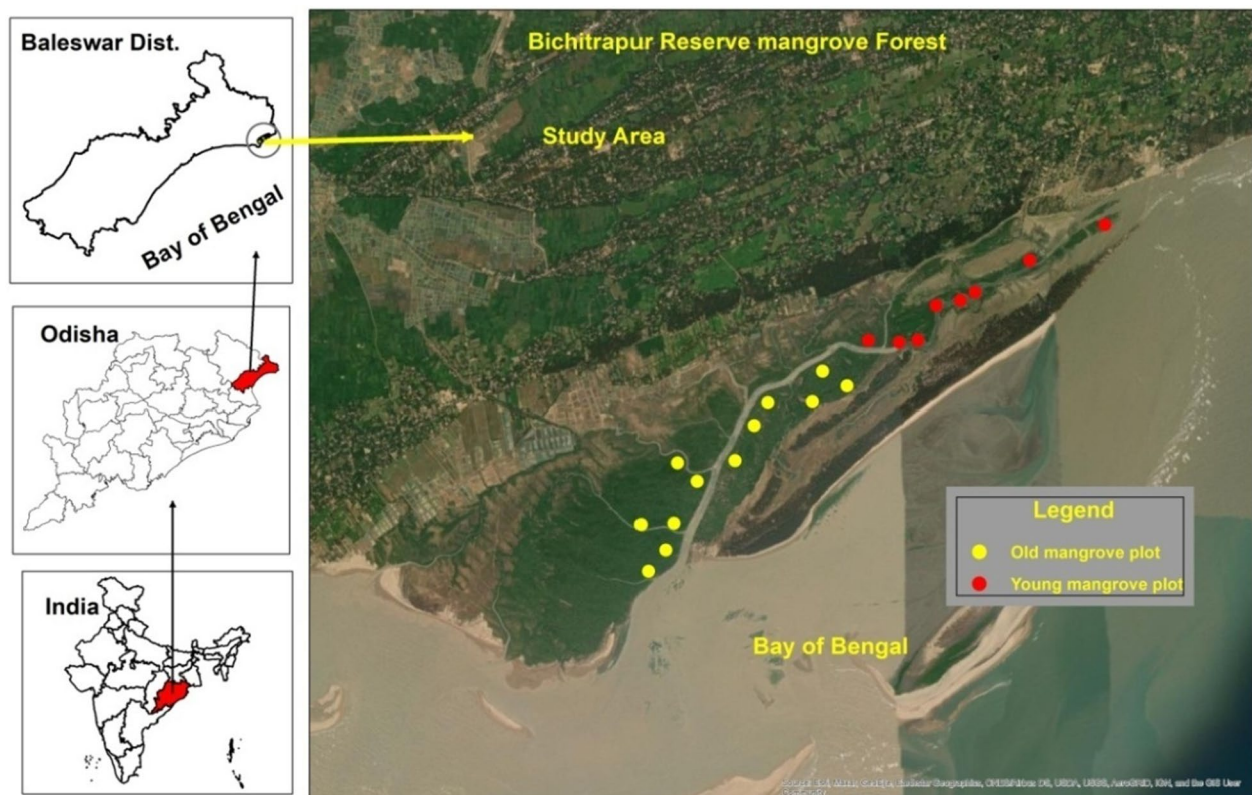


Fig. 1 Location of Bichitrapur mangrove reserve forest and distribution of sampling plots

the lowest (18 °C) in December, whereas annual rainfall ranges between 1100 and 1300 mm with the highest rainfall during August (~ 600–700 mm) and relative humidity ranges between 50 and 90%.

Vegetation sampling

To understand the floristic diversity of BMRF, altogether six seasonal field investigations (i.e., two each in pre-monsoon, monsoon, and post-monsoon) were conducted between January 2022 and December 2023. The existing mangrove vegetation was categorized into two classes: (i) Old natural stands (i.e., older than 50 years) and (ii) Young planted stands (i.e., ~ 20 years). The old stands were well protected and undisturbed, whereas in young stands, selective species were planted to increase the mangrove forest cover of BMRF. Random sampling plots were established to achieve the ecological data on forest attributes, i.e., 12 and 8 plots in old natural and young planted forest stands (plot size: 25 × 20 m; total area sampled: 10000 m²) (Fig. 1). Species were identified and forest attributes such as species richness, their total count, plant height (h), and circumference at breast height (cbh) were measured at 1.3 m above the ground of woody mangroves (trees and shrubs) with a minimum cbh value of 8 cm. The plant dbh was derived from the cbh value (i.e., dbh = cbh/Pi). The forest ecological attributes such as plant density (d), abundance (A), frequency (F), basal area (BA), Importance Value Index (IVI), and Relative Importance Value Index (RIVI) of young and old stands were estimated as suggested by Curtis and McIntosh (1950), Curtis (1959), Cintron and Schafer-Novelli (1984) as follows:

$$\text{Density} = \frac{\text{Total individuals recorded from all plots}}{\text{Total no of plots sampled}} \quad (1)$$

$$\text{Abundance} = \frac{\text{Total number of individuals of a species}}{\text{Number of plots in which the species occurred}} \quad (2)$$

$$\text{Frequency (\%)} = \frac{\text{No. of plots in which a species occurs}}{\text{Total no of plots}} \times 100 \quad (3)$$

$$\text{Basal area (or dominance)} = \frac{\pi D^2}{4} \quad (4)$$

$$\text{Importance Value Index (IVI)} = \text{Relative density} + \text{Relative frequency} + \text{Relative dominance} \quad (5)$$

$$\text{Relative Importance Value Index (RIVI)} = \frac{\text{IVI of the species}}{300} \times 100 \quad (6)$$

The species diversity and their distribution were estimated using the Shannon-Wiener index (H') (Shannon and Wiener 1963); the Pielou evenness index (EI) (Pielou 1975) as follows:

$$\text{Shannon - Wiener index } (H') = - \sum P_i \log_n P_i \quad (7)$$

where,

$$P_i = \frac{\text{Number of individuals of one species}}{\text{Total number of all individuals}} \quad (8)$$

$$\text{Pielou evenness Index (EI)} = \frac{H'}{\ln S} \quad (9)$$

where H' is the Shannon-Wiener index of the community and S is the total number of species in the community.

Soil sampling and analysis

A composite soil sample was prepared by mixing randomly collected soils at four locations from each plot at 30 cm depth. Soil pH and electrical conductivity (EC) were measured using the pH and conductivity meter of a supernatant saturated suspension (w/w soil:water: 1:2.5). Available soil organic carbon (SOC) was estimated using the Walkley and Black (1934) method; nitrogen (N) by the Kjeldahl procedure; phosphorus (P) by Olsen and Sommers (1982); and potassium (K) using a flame photometer. SOC was determined as follows:

$$\begin{aligned} \text{SOC} \left(t \text{ ha}^{-1} \right) \\ = \text{soil bulk density} * \text{soil depth} * \text{organic carbon\%} \end{aligned} \quad (10)$$

whereas soil bulk density (BD) was determined as the ratio of dry weight of soil (g) to its volume (cm³).

Estimation of stand biomass and carbon

To estimate the stand biomass, aboveground biomass (AGB) + belowground biomass (BGB) of woody mangroves (dbh > 2.5 cm), we used common allometric equations of Komiyama et al. (2005) which are suitable for biomass estimation of Southeast Asian countries. The plant dbh, and wood specific density are used as predictive variable in these allometric equations with the coefficient of determination (R^2) of 0.979 and 0.954, respectively (Ragavan et al. 2021). The allometric equations used are:

$$AGB(kg) = 0.251\rho dbh^{2.46} \quad (11)$$

$$BGB(kg) = 0.199\rho^{0.899} dbh^{2.22} \quad (12)$$

where dbh is tree diameter at breast height (in cm), and ρ is wood-specific density ($g\ cm^{-3}$). To increase the accuracy of biomass estimation, we used species-specific ρ values that were obtained from the World Agroforestry Database (Source: <http://db.worldagroforestry.org/>). A conversion factor of 0.48 and 0.39 was used to convert AGB and BGB to their constituent carbon, respectively (Kauffman and Donato 2012). The total 'C' stock in biomass (i.e., AGB 'C' + BGB 'C') was estimated for plots and entire forested area by extrapolating with average biomass 'C' value with the total mangrove forest area of BMRF and Subarnarekha estuary (i.e., 5.4 km²) (FSI 2021). The TECS was calculated as the sum of biomass carbon stock and soil carbon stock. The estimated 'C' stock was converted into CO₂ equivalents by multiplying with the factor of 3.67 (Kauffman and Donato 2012).

Statistical analysis

We used statistical software like XLSTAT and SPSS 17.0 to achieve our results. A Pearson's correlation analysis was performed using forest attributes (i.e., species richness, tree density, height, basal area, IVI, species diversity, biomass, and soil parameters) for overall BMRF. Major structural forest attributes, like, d, BA, IVI, were used to understand the strength of correlation with biomass of two different stand ages. The linear regression equations were developed using density, BA, and IVI with biomass of species recorded from two forest stand ages. Mean $\pm$ standard error was presented.

Results

Floristic diversity and forest structural attributes

We recorded twenty-nine species consisting of eighteen exclusive and eleven associate species that were distributed in 15 families and 22 genera, i.e., exclusive mangroves: 8 families and 12 genera; mangrove associates: 7 families and 11 genera (Table 1; Supplementary Fig. 1a & 1b). Among exclusive species, the highest richness was recorded from Rhizophoraceae (7 species), followed by Acanthaceae (4 species) and Lythraceae (2 species), whereas among the associates, Fabaceae showed the highest richness (4 species), followed by Aizoaceae (2 species). Overall, 23 species fell into the IUCN red list category, while 3 species, i.e., *Aegialitis rotundifolia* and *Ceriops decandra* (NT), and *Heritiera fomes* (EN) were in the global category of threatened species. All listed exclusive mangroves were trees or shrubs except *Acanthus ilicifolius*, a spiny herb.

The occurrence of exclusive mangroves such as *Aegialitis rotundifolia*, *Bruguiera gymnorhiza*, *Bruguiera sexangula*, *Ceriops decandra*, *Kandelia candel*, *Rhizophora apiculata*, *Rhizophora mucronata*, *Heritiera fomes*, and *Sonneratia caseolaris* was very sporadic and restricted. As a whole, BMRF ranks 3rd in terms of mangrove species diversity in the state, after Bhitarkanika National Park and mangroves of Mahanadi delta in Odisha state, India.

In this study, ecological and forest structural results of 10 exclusive woody mangrove species were achieved. The mean tree density (d) of the young and old stand was 3165 ha⁻¹ and 1798 ha⁻¹, respectively (Table 2). In the young stand, the highest 'd' was recorded for *Aegiceras corniculatum* (770 ha⁻¹), whereas in the old natural stands, the highest 'd' was recorded for *Avicennia marina* (603 ha⁻¹). The 'd' of *Xylocarpus granatum*, *Ceriops decandra*, *Bruguiera cylindrica*, *Heritiera fomes* were comparatively lower. Lowest frequency (F) and abundance (A) were estimated for *Ceriops decandra* (12.5) and *Xylocarpus granatum* (7.5) for young mangrove stand, whereas *Bruguiera cylindrica* (8.3) and *Xylocarpus granatum* (3) from old forest stand. The overall basal area (BA) of young and older stands was 18.8 m² ha⁻¹ and 45.4 m² ha⁻¹, respectively. Highest relative dominance (RD) was shown by *Avicennia marina* in both types of forest stands (young: 31.05; old: 43.37). For young stand, the highest IVI was recorded for *Avicennia marina* (68.39), followed by *Aegiceras corniculatum* (49.58), *Avicennia officinalis* (45.13) and *Sonneratia apetala* (45.07). *Bruguiera cylindrica*, *Ceriops decandra* and *Xylocarpus granatum* contributed little to the overall forest structure (IVI < 5). The mean ($\pm$ SE) richness, *H'* and EI of young and old forest stands of BMRF were 5.13 $\pm$ 0.64 and 4.67 $\pm$ 0.51, 1.37 $\pm$ 0.13 and 1.18 $\pm$ 0.15, 0.84 $\pm$ 0.04 and 0.77 $\pm$ 0.05, respectively (Table 3).

Soil characteristics

The mean soil pH and conductivity of young stand and old stands were 6.78 $\pm$ 0.05 and 257.57 $\pm$ 5.43 μ S, and 6.68 $\pm$ 0.06 and 252.67 $\pm$ 7.49 μ S, respectively (Fig. 2). For young stands, the available soil N, phosphorus and potassium were 102.15 $\pm$ 4.12 kg ha⁻¹, 10.22 $\pm$ 0.26 kg ha⁻¹, 652.24 $\pm$ 36.29 kg ha⁻¹ whereas for the old forest stands, the estimated value was 155.89 $\pm$ 10.54 kg ha⁻¹, 11.69 $\pm$ 0.48 kg ha⁻¹ and 1066.01 $\pm$ 65.63 kg ha⁻¹, respectively (Fig. 2). The mean soil carbon pool (at 30 cm depth) of the young stand was 40.20 $\pm$ 1.24 t ha⁻¹, whereas it was 49.68 $\pm$ 2.39 t ha⁻¹ for the old stand (Fig. 2; supplementary Table 1).

Table 1 Floristic diversity of Bichitrapur mangrove reserve forest, Odisha, India

Sl. No	Plant species	Family	IUCN status	Life forms
Exclusive mangrove				
1	<i>Aegialitis rotundifolia</i> Roxb	Plumbagenaceae	NT	Small tree
2	<i>Aegiceras corniculatum</i> (L.) Blanco	Myrsinaceae	LC	Shrub
3	<i>Acanthus ilicifolius</i> L.	Acanthaceae	LC	Herb
4	<i>Avicennia alba</i> Blume		LC	Tree
5	<i>Avicennia marina</i> (Forsk.) Veierh		LC	Tree
6	<i>Avicennia officinalis</i> L.		LC	Tree
7	<i>Bruguiera cylindrical</i> (L.) Blume	Rhizophoraceae	LC	Small tree
8	<i>Bruguiera gymnorhiza</i> (L.) Lam. Ex Savigny		LC	Tree
9	<i>Bruguiera sexangula</i> (Lour.) Poir		LC	Tree
10	<i>Ceriops decandra</i> (Griff.) Ding Hou		NT	Shrub
11	<i>Kandelia candel</i> (L) Druce		LC	Tree
12	<i>Rhizophora apiculata</i> Blume		LC	Tree
13	<i>Rhizophora mucronata</i> Lamk		LC	Tree
14	<i>Excoecaria agallocha</i> L.	Euphorbiaceae	LC	Tree
15	<i>Heritiera fomes</i> Buch. -Ham	Sterculiaceae	EN	Tree
16	<i>Sonneratia apetala</i> Buch. – Ham	Lythraceae	LC	Tree
17	<i>Sonneratia caseolaris</i> (L.) Engl		LC	Tree
18	<i>Xylocarpus granatum</i> Koenig	Meliaceae	LC	Tree
Mangrove associate				
1	<i>Dalbergia spinosa</i> Roxb	Fabaceae	LC	Scrambling shrub
2	<i>Derris trifoliata</i> Lour		--	Liana
3	<i>Pongamia pinnata</i> (L.) Pierre		LC	Tree
4	<i>Ticanto crista</i> (L.) R.Clark & Gagnon		--	Climbing shrub
5	<i>Hibiscus tiliaceus</i> L.	Malvaceae	LC	Tree
6	<i>Opuntia tuna</i> (L.) Mill	Cactaceae	--	Succulent shrub
7	<i>Oryza coarctata</i> Roxb	Poaceae	DD	Perennial geophyte
8	<i>Sesuvium portulacastrum</i> (L.) L.	Aizoaceae	LC	Herb
9	<i>Trianthema portulacastrum</i> L.			
10	<i>Suaeda maritima</i> (L.) Dumort	Amaranthaceae	--	Sub-shrub
11	<i>Volkameria inermis</i> L.	Lamiaceae	--	Climber
Total	29 species (18 exclusive and 11 associate mangroves)			

NT Near threatened, DD Data deficient, EN Endangered, LC Least concerned

Mangrove biomass and total ecosystem carbon stock

In BMRF, the mean ($\pm$ SE) total biomass (TB: AGB + BGB) for young and old stands was 165.31 ± 20.89 t ha⁻¹ and 586.12 ± 56.74 t ha⁻¹, respectively (Table 3). For overall BMRF, the mean AGB, BGB, TB and TBC were 297.60 ± 42.86 t ha⁻¹, 120.61 ± 15.64 t ha⁻¹, 417.79 ± 58.48 t ha⁻¹, and 189.72 ± 26.66 t 'C' ha⁻¹, respectively. Among species, *Avicennia marina* had the highest biomass carbon pool in both the forest stand ages, i.e., young planted stand: 36% and old natural stand: 48% (Table 2; Fig. 3a). Together, three species of *Avicennia* (i.e., *Avicennia alba*, *Avicennia marina*, and *Avicennia officinalis*) contributed 70% and 93% of TBC in planted young and old natural forest stands of BMRF, respectively. *Bruguiera cylindrical*,

Xylocarpus granatum, *Heritiera fomes* and *Ceriops decandra* contributed least to the forest biomass (<1%) (Fig. 3a). The biomass CO₂ equivalence of the old stand was five times larger than the younger stand (Table 3). Among the studied species, the CO₂ e of species from *Avicennia* and *Sonneratia apetala* was higher than others. This indicates that they are the most potential mangrove species of the BMRF and Subarnarekha estuary in terms of standing blue carbon stock and thus their degradation will lead to the release of significantly high greenhouse gases (Fig. 3b). For BMRF, the AGB represented 68–72% of TB, while the BGB represented 28–32% of TB (Fig. 3c). The contribution of vegetation and soil to TECS was 63% and 37% in the young stand, whereas in

Table 2 Structural pattern and biomass stocks of two forest stand ages of Bichitrapur mangrove reserve forest

SI	Species	d	F	A	BA	Rd	Rf	RD	IVI	RIVI	AGB t ha ⁻¹	BGB	TB	TBC
Young planted mangrove stand (~ 20 year old)														
1	<i>Avicennia alba</i>	378	62.5	75.50	2.26	11.95	12.20	12.04	36.18	12.06	14.29	6.82	21.10	9.52
2	<i>Avicennia marina</i>	718	75.0	119.58	5.84	22.71	14.63	31.05	68.39	22.80	40.86	18.86	59.72	26.97
3	<i>Avicennia officinalis</i>	393	75.0	65.42	3.40	12.42	14.63	18.07	45.13	15.04	23.99	11.06	35.05	15.83
4	<i>Sonnerati aapetala</i>	318	87.5	45.36	3.37	10.05	17.07	17.95	45.07	15.02	17.79	8.30	26.09	11.78
5	<i>Aegiceras corniculatum</i>	770	87.5	110	1.53	24.37	17.07	8.14	49.58	16.53	6.24	3.50	9.74	4.36
6	<i>Excoecaria agallocha</i>	415	50.0	103.75	1.97	13.13	9.76	10.50	33.39	11.13	7.04	3.69	10.73	4.82
7	<i>Bruguiera cylindrica</i>	100	37.5	33.33	0.29	3.16	7.32	1.52	12.00	4.00	1.77	0.92	2.69	1.21
8	<i>Xylocarpus granatum</i>	15	25.0	7.50	0.03	0.47	4.88	0.18	5.54	1.85	0.16	0.09	0.25	0.11
9	<i>Ceriops decandra</i>	55	12.5	55	0.10	1.74	2.44	0.55	4.73	1.58	0.50	0.28	0.78	0.35
Total (ha ⁻¹)		3165	512.5	620.44	18.80	100	100	100	300	100	112.64	53.52	166.15	74.94
Old natural mangrove stand (~ 50 year old)														
1	<i>Avicennia alba</i>	312	91.67	17.00	12.76	17.33	19.64	28.10	65.08	21.69	122.52	47.03	169.55	77.15
2	<i>Avicennia marina</i>	603	100	30.17	19.74	33.55	21.43	43.47	98.45	32.82	188.32	73.96	262.28	119.24
3	<i>Avicennia officinalis</i>	182	83.33	10.90	8.13	10.10	17.86	17.90	45.86	15.29	83.88	31.71	115.58	52.63
4	<i>Sonneratia apetala</i>	40	33.33	6.00	1.50	2.22	7.14	3.30	12.67	4.22	10.58	4.24	14.82	6.73
5	<i>Aegiceras corniculatum</i>	348	58.33	29.86	1.03	19.37	12.50	2.27	34.14	11.38	4.78	2.51	7.29	3.28
6	<i>Excoecaria agallocha</i>	240	50.00	24.00	1.80	13.35	10.71	3.96	28.02	9.34	7.20	3.56	10.76	4.84
7	<i>Bruguiera cylindrica</i>	27	8.33	16.00	0.04	1.48	1.79	0.09	3.36	1.12	0.21	0.12	0.33	0.15
8	<i>Xylocarpus granatum</i>	10	16.67	3.00	0.02	0.56	3.57	0.05	4.18	1.39	0.37	0.18	0.55	0.25
9	<i>Heritiera fomes</i>	37	25.00	7.33	0.39	2.04	5.36	0.85	8.25	2.75	3.43	1.52	4.94	2.24
Total (ha ⁻¹)		1798	466.67	144.26	45.40	100	100	100	300	100	421.30	164.82	586.12	266.50

d tree density (Total number of individuals of each species which had (dbh > 2.5 cm), *F* Frequency, *A* Abundance, *BA* Basal area or dominance ((m² ha⁻¹), *Rd* Relative density, *Rf* Relative frequency, *RD* Relative dominance, *IVI* Importance Value Index, *RIVI* Relative IVI, *AGB* Aboveground biomass, *BGB* Belowground biomass, *TB* Total biomass, *TBC* Total biomass carbon

the old stand it was 83% and 17% (Fig. 3d). Overall, the mean TECS was 235.62 ± 27.34 t C ha⁻¹, whereas it varied between $87.46 - 155.13$ t C ha⁻¹ in young stands (mean: 114.76 ± 10.01 t C ha⁻¹) and $211.79 - 449.51$ t C ha⁻¹ in old stands (mean: 316.19 ± 25.17 t C ha⁻¹) (Table 3).

Correlation analysis

The correlation study of forest attributes and soil parameters revealed that mean stand height ($r=0.87$), BA ($r=0.99$), soil nitrogen ($r=0.76$), soil K ($r=0.78$), and soil 'C' % ($r=0.80$) were significantly positive correlated with TB at $p<0.01$ (Table 4). But, H' ($r=-0.57$), d ($r=-0.61$), and BD ($r=-0.78$) were significantly negatively correlated ($p<0.01$) with TB whereas α ($r=-0.50$), and EI ($r=-0.50$) were significantly negatively correlated ($p<0.05$) with TB. However, stand height ($r=-0.80$), TB ($r=-0.61$), N ($r=-0.61$), K ($r=-0.64$), soil C ($r=-0.69$) and SOC ($r=-0.58$) showed significant negative correlation ($p<0.01$) with tree density. We found a significant positive correlation of diversity attributes such as H' ($r=0.91$) and EI ($r=0.88$) with α (richness) ($p<0.01$). The soil C showed a positive relation with stand height (0.85), BA (0.77), TB (0.80), soil N (0.75) at $p<0.01$ and

with soil P (0.47), and K (0.61) at $p<0.05$ (Table 4). No significant relation was found between soil pH and EC with other attributes. The linear regression and correlation study of d , BA and IVI of individual species with respective TB resulted in a strong positive relationship between old stands and young stands (Fig. 4a–f). In the young stand, BA (R^2 : 0.96) and IVI (R^2 : 0.738) showed significant positive relations with TB, whereas in the old stand, d (R^2 : 0.629), BA (R^2 : 0.996) and IVI (R^2 : 0.908) showed significant positive relation with TB at $p<0.01$ (Fig. 4a–f; Table 5).

Discussion

Floristic diversity and stand attributes

The BMRF hosts 18 exclusive mangrove species against an overall Odisha and Indian record of 35 and 42, respectively (Ragavan et al. 2016). The overall species diversity of BMRF is higher than in mangrove-bearing Indian states such as Tamilnadu, Puducherry, Karnataka, Goa, Gujarat, and Kerala (Ragavan et al. 2016). Past studies have reported that planted forests could have more species than natural forests as the former is a selective practice which could introduce new different species

Table 3 Spatial variation of forest attributes across the sampling plots of Bichitrapur mangrove reserve forest, India

Plots	α	H'	El	d (ha ⁻¹)	BA (m ² ha ⁻¹)	AGB t ha ⁻¹	BGB	TB	TBC	TECS	CO ₂ e
Y1	3	0.79	0.72	4140	26.01	163.53	78.83	242.35	109.23	150.98	554.08
Y2	5	1.49	0.93	3040	20.70	123.87	58.80	182.66	82.39	124.32	456.24
Y3	5	1.52	0.95	3920	20.86	120.43	58.54	178.97	80.64	126.34	463.68
Y4	6	1.66	0.93	2560	15.38	78.77	38.42	117.19	52.79	92.05	337.84
Y5	8	1.65	0.79	3680	15.07	80.64	40.05	120.69	54.33	87.46	320.99
Y6	3	0.89	0.64	2120	23.47	176.86	78.05	254.91	115.33	155.13	569.33
Y7	4	1.18	0.85	3800	15.30	68.59	34.71	103.30	46.46	86.32	316.80
Y8	7	1.76	0.91	2060	13.64	83.89	38.47	122.36	55.27	95.48	350.41
Mean ± SE	5.13 ± 0.64	1.37 ± 0.13	0.86 ± 0.04	3165 ± 295	18.80 ± 1.62	112.07 ± 14.54	53.23 ± 6.39	165.31 ± 20.89	74.56 ± 9.46	114.76 ± 10.01	421.17 ± 36.73
O1	2	0.27	0.39	1560	61.29	577.01	224.20	801.21	364.40	408.34	1498.59
O2	4	1.15	0.83	820	28.47	288.94	109.04	397.99	181.22	231.76	850.57
O3	2	0.50	0.72	1100	60.89	643.36	238.35	881.71	401.77	449.51	1649.68
O4	6	1.06	0.59	3440	37.43	332.96	130.48	463.45	210.71	244.75	898.23
O5	3	0.58	0.52	1760	61.41	586.22	229.36	815.59	370.84	422.34	1550.00
O6	3	0.77	0.70	1720	56.68	534.39	210.39	744.78	338.56	382.55	1403.96
O7	5	1.51	0.94	1860	38.13	327.62	134.08	461.70	209.55	273.44	1003.51
O8	6	1.67	0.93	1540	31.71	264.09	106.44	370.53	168.27	229.97	843.98
O9	6	1.65	0.92	2280	54.68	503.49	196.20	699.69	318.19	360.96	1324.72
O10	6	1.60	0.89	1840	33.77	283.13	115.09	398.22	180.79	235.22	863.26
O11	6	1.67	0.93	1700	49.08	458.95	178.20	637.15	289.79	343.61	1261.07
O12	7	1.73	0.89	1960	31.76	255.39	106.04	361.43	163.94	211.79	777.26
Mean ± SE	4.67 ± 0.51	1.18 ± 0.15	0.77 ± 0.05	1798 ± 185	45.44 ± 3.78	421.30 ± 41.48	164.82 ± 15.30	586.12 ± 56.74	266.50 ± 25.87	316.19 ± 25.17	1160.40 ± 92.38

Y Young plantation plot and O Old natural forest plot

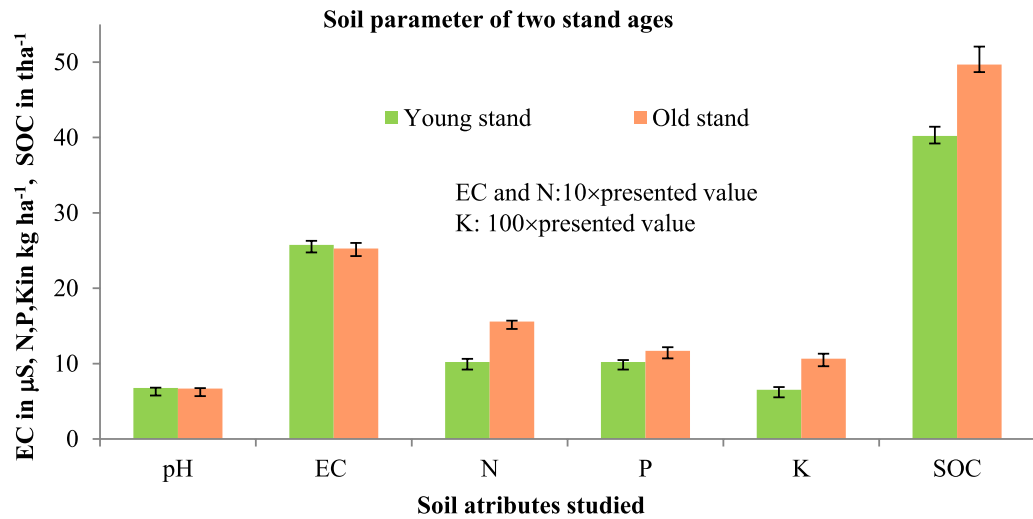


Fig. 2 Soil parameters across two stand ages of the Bichitrapur mangrove reserve forest. (Mean ± SE)

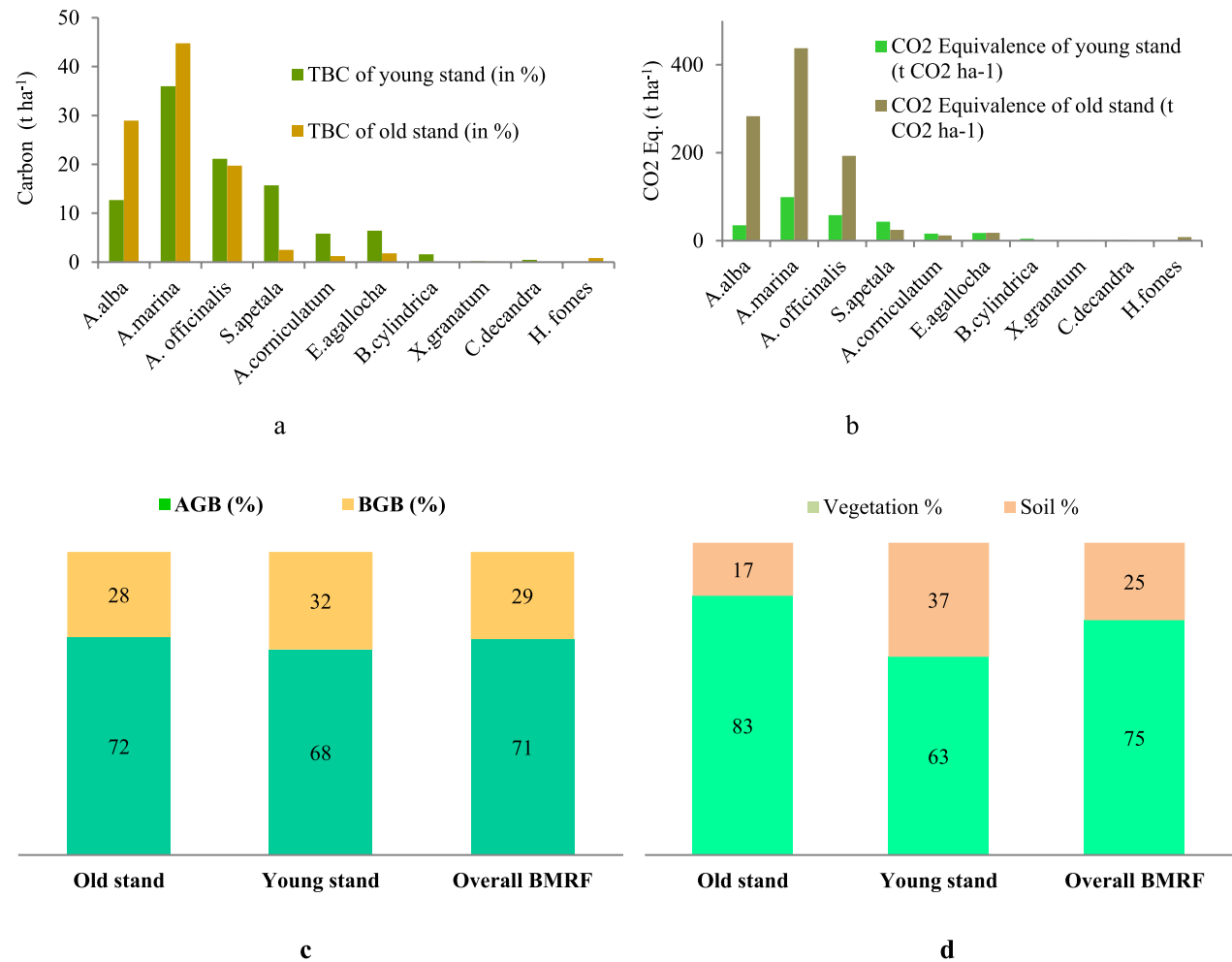


Fig. 3 The relative variation of forest attributes across stand ages. **a** Species-wise contributions of total biomass carbon (TBC) in young and old stand; **b** Species-wise contributions of CO₂ equivalence in young and old stand; **c** Contribution of AGB and BGB to total vegetation biomass (in %); **d** Contribution of biomass (or vegetation) and soil carbon to total ecosystem carbon stock (in %)

Table 4 Pearson's correlation matrix of forest attributes, and soil parameters for overall Bichitrapur mangrove reserve forest

Attributes	α	H'	d	El	h	BA	TB	EC	pH	N	P	K	C	BD	SOC
α	1														
H'	0.907**	1													
d	0.225	0.163	1												
El	0.629**	0.877**	0.100	1											
h	-0.521*	-0.502*	-0.797**	-0.313	1										
BA	-0.502*	-0.568**	-0.556*	-0.509*	0.832**	1									
TB	-0.504*	-0.572**	-0.613**	-0.503*	0.873**	0.994**	1								
EC	0.179	0.311	0.115	0.312	-0.147	-0.047	-0.098	1							
pH	0.052	0.038	0.145	-0.027	-0.228	-0.302	-0.302	0.229	1						
N	-0.327	-0.313	-0.612**	-0.158	0.792**	0.732**	0.767**	-0.159	-0.374	1					
P	-0.014	-0.056	-0.164	-0.073	0.262	0.376	0.368	0.399	-0.186	0.521*	1				
K	-0.355	-0.471*	-0.637**	-0.506*	0.751**	0.765**	0.776**	0.029	0.027	0.556*	0.166	1			
C	-0.299	-0.257	-0.687**	-0.146	0.846**	0.767**	0.798**	-0.109	-0.203	0.747**	0.474*	0.609*	1		
BD	0.287	0.403	0.475*	0.425	-0.657**	-0.742**	-0.777**	0.396	0.165	-0.637**	-0.432	-0.540*	-0.794**	1	
SOC	-0.074	-0.131	-0.582**	0.286	0.552**	0.332	0.338	0.250	-0.172	0.429	0.279	0.351	0.673**	-0.106	1

α Species richness, H' Shannon-Wiener index, d Tree density, E Pielou's evenness index, h tree height, BA Basal area, TB Total biomass, EC Electrical conductivity of soil, pH soil pH, N Soil available nitrogen, P Soil available phosphorous, K Soil potassium, C Soil carbon, BD Soil bulk density, SOC Soil organic carbon

* Correlation is significant at the 0.05 level (2-tailed), **Correlation is significant at the 0.01 level (2-tailed)

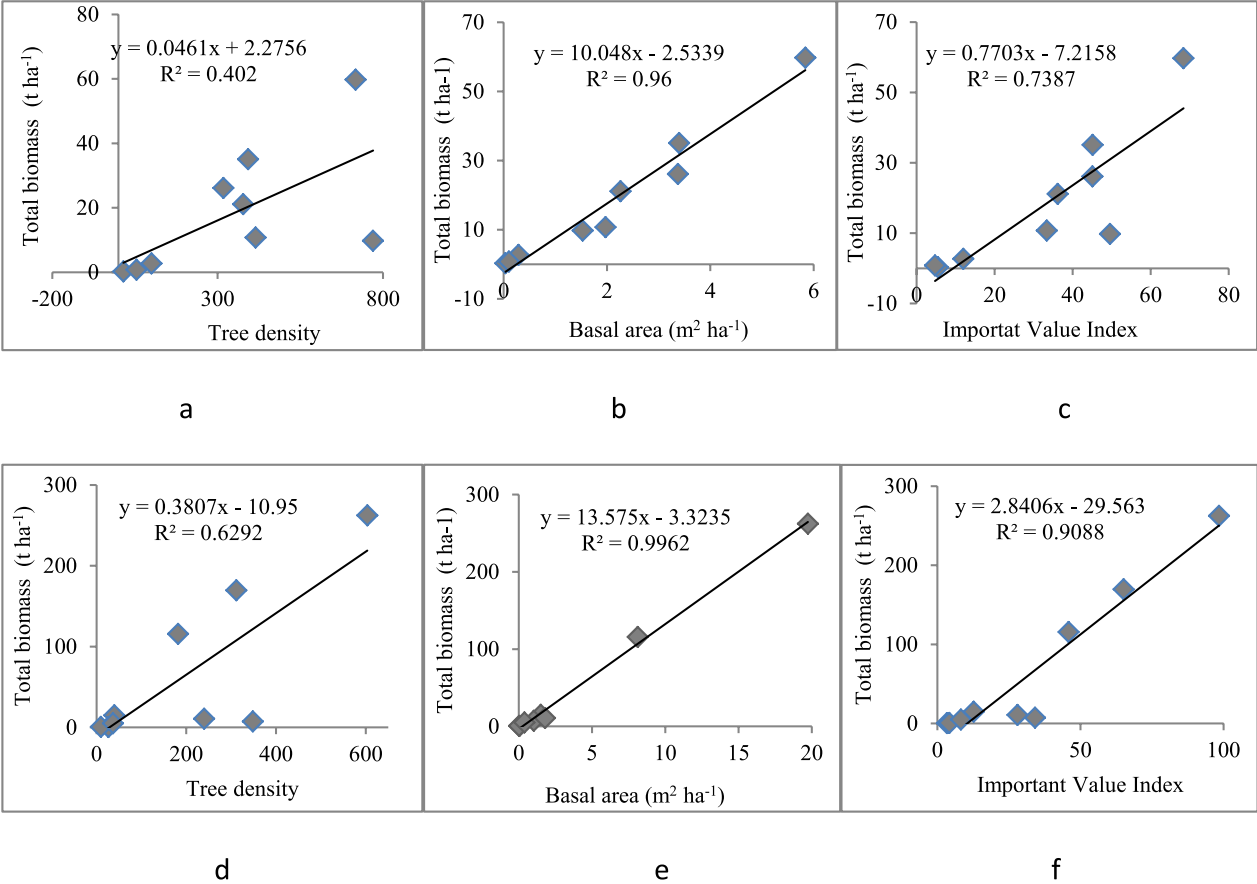


Fig. 4 Linear regression relationship derived by using individual species forest attributes across two stand ages. **a–c** Linear regression relationship of tree density, basal area, and Importance Value Index with total biomass for mangrove species of young stands, respectively; **d–f** Linear regression relationship of tree density, basal area, and Importance Value Index with total biomass for mangrove species of old stands, respectively

to the site (Hong 2001; Nam et al. 2016). However, this study didn't record any difference in species richness except that *Ceriops decandra* was only recorded in planted stands and *Heritiera fomes* in old natural forest stands. The IVI acts as a good indicator of understanding species dominance in forest communities. The IVI results revealed that the species' dominance was less

prominent in young stand than old stand. Altogether, six species (*Avicennia alba*, *Avicennia marina*, *Avicennia officinalis*, *Sonneratia apetala*, *Aegiceras corniculatum*, and *Excoecaria agallocha*) in young stand, whereas only four species (*Avicennia alba*, *Avicennia marina*, *Avicennia officinalis*, *Sonneratia apetala*) in old stand had RIVI > 10 (Table 2). The species dominance also differed compared to other Indian mangrove sites as the mangrove species like, *Heritiera fomes*, *Excoecaria agallocha* and *Avicennia officinalis* dominate on the eastern coast; *Rhizophora sp.* and *Avicennia officinalis* on the west coast and species from mangrove family Rhizophoraceae predominated the Island mangroves like, Andaman and Nicobar Islands (George et al. 2018; Sreelekshmi et al. 2018; Kiruba-Sankar et al. 2018; Harishma et al. 2020; Kripa et al. 2021; Panda et al. 2024). The stands 'd' and 'BA' of BMRF showed similarity with mangrove forests such as Sundarbans, Bangladesh (Kamruzzaman et al. 2018), Kerala (George et al. 2018; Sreelekshmi et al. 2018; Harishma et al. 2020), Andaman Islands (Kiruba-Sankar et al. 2018), Kachchh, Gujarat (Thivakaran et al. 2003),

Table 5 Pearson's correlation matrix across stand ages using species specific forest attributes

		Old natural stand →			
		TB	d	BA	IVI
Young planted stand ↓	TB	1	0.794*	0.998**	0.953**
	d	0.634	1	0.817**	0.931**
	BA	0.980**	0.699*	1	0.964**
	IVI	0.859**	0.912**	0.915**	1

TB Total biomass, d Tree density, BA Basal area, IVI Importance Value Index
* Correlation is significant at the 0.05 level (2-tailed), **Correlation is significant at the 0.01 level (2-tailed)

and Bhitarkanika (Panda et al. 2024). BA is a good indicator of knowing the growing forest age, succession stage, disturbance, and production of biomass (Murthy et al. 2022). The lower BA estimated for the young planted mangrove stand of BMRF was due to the presence of small trees with lower dbh value (Kamruzzaman et al. 2018; Ahmed et al. 2023). However, the high BA of old natural mangrove stands has resulted from the existence of large tree species such as *Avicennia alba*, *Avicennia marina*, and *Avicennia officinalis* with relatively higher dbh than planted stands (Nam et al. 2016). The BA of old forest stands of BMRF showed similarity with Bhitarkanika (Panda et al. 2024) and Andaman and Nicobar Islands (Kiruba-Sankar et al. 2018), but, higher than Sundarbans (Kamruzzaman et al. 2018; Joshi and Ghose 2003; Ahmed et al. 2023), Kerala (George et al. 2018; Sreelekshmi et al. 2018; Harishma et al. 2020), and Coringa mangroves, Andhra Pradesh (Satyanarayana et al. 2002). The resulting diversity indices, like H' of young stand and old stand, were lower than other Indian mangroves (Sreelekshmi et al. 2020; Kiruba-Sankar et al. 2018; Panda et al. 2024). However, the H' and EI of young stands were higher than old stands, indicating more even species distribution and dominance in the former forest stands.

Mangrove biomass and relative carbon stock

Mangrove forests sequester 3–5 times higher atmospheric CO_2 than the counter-terrestrial forests that recognize them as a high potential C sink forest ecosystem in the world (Lee et al. 2014). The biomass attribute, AGB, is a good indicator of ecosystem productivity, age, allocation of organic matter and exportation (Kasawani et al. 2007). The annual increment of AGB ranges from 4 t ha^{-1} year $^{-1}$ in a 7-year-old *Avicennia*-dominated forest (Day et al. 1996) to 26.7 t ha^{-1} year $^{-1}$ in a natural *Rhizophora apiculata*-dominated forest (Christensen 1978). Factors such as type of species, season (light quality, durations, etc.) and age affect the photosynthetic CO_2 sequestration rate in mangrove forest. In Indian conditions, *Rhizophora mucronata* showed the maximum rate of CO_2 sequestration in summer, whereas *Sonneratia apetala* showed higher values in post-monsoons (Lele et al. 2021). As stand ages, the carbon accumulation rate at 4, 5, 8, 10-year *Sonneratia apetala* plantations has increased from 5.0, 7.9, 8.7, 8.4 t ha^{-1} year $^{-1}$, respectively (Ren et al. 2010). Our estimated mean AGB of young stands and old stands was in the global range (Hutchison et al. 2014; Supplementary Fig. 2). The quantified biomass variables, like AGB, BGB and TB of old stands, were higher than natural mangrove stands of Botoc mangrove forest, Philippines (Abino et al. 2014), Klang islands, Peninsular Malaysia (Rozainah et al. 2018), Kerala (Harishma et al. 2020), Sundarban (Kamruzzaman

et al. 2017) and similar to the corresponding mean value estimated for mangroves of Andaman Islands (Ragavan et al. 2021). The mono-species plantation of different species at same stand age showed significant variation in biomass stock at Ayeyarwady Delta, Myanmar (Thant et al. 2012). Within the same stand age (i.e., six years of plantation), *Sonneratia apetala* had achieved the highest biomass stock (101.0 ± 17.1 t ha^{-1}), followed by *Avicennia marina* (52.3 ± 10.3 t ha^{-1}) and *Avicennia officinalis* (46.8 ± 11.6 t ha^{-1}) (Thant et al. 2012). In BMRF, *Avicennia marina* acquired the highest stand biomass across the two stand ages, followed by *Avicennia officinalis* and *Sonneratia apetala* in young stand and *Avicennia alba* and *Avicennia officinalis* in old stands. The intra-species comparison showed an increase in biomass stock with stand ages; especially those are large trees such as *Avicennia alba*, *Avicennia marina*, *Avicennia officinalis*, compared to understory small trees and shrub species like, *Agave corniculatum*, *Excoecaria agallocha*, *Bruquiera cylindrica* and *Xylocarpus granatum*. However, *Sonneratia apetala* showed deviation in the trend that it had higher biomass in young stand than old stand, possibly due to selective plantation that presented a higher plant density in young stand compared to old stand (Table 2). In BMRF, the relative contribution of biomass of the genus *Avicennia* was 70% in plantation stand and 93% in old natural stand whereas it accounted for 57% of the forest biomass in the world's largest mangrove forest, the Sundarban (Barik et al. 2021) and only 6% in Andaman Islands, India (Ragavan et al. 2021). The mean AGB carbon (or AGB 'C') stock of BMRF was approximately two times higher than the global mean AGB 'C' (Estrada and Soares 2017) and about three times higher than the western coast mangrove of Kerala state (Shreelekshmi et al. 2022). The biomass 'C' stock of old natural stands of BMRF was higher than the Indian mangrove stands of Kerala and South Andaman and Baratang Island of the Andaman Islands (Harishma et al. 2020; Ragavan et al. 2021).

The forest biomass and C stock increases with stand age (Ren et al. 2010). Growing plants in forests sequester more atmospheric CO_2 in the form of biomass than old forests (Walcker et al. 2018). The early colonizing species grow faster, accumulate more biomass, and the photosynthesis/respiration ratio is larger than the mature ecosystem of large biomass but little net production (Alongi 2011). Stand biomass is also determined by the type of mangrove species growing in the forest. It was evident that when *Sonneratia apetala* and *Kandelia obovata* were planted during an afforestation program with the same initial density, and after 6 years, *Sonneratia apetala* gained higher AGB and BGB relative to *Kandelia obovata* (Lunstrum and Chen 2014). After plantation, *Sonneratia*

apetala achieved fast growth, high biomass accumulation and high carbon storage capacity (Ren et al. 2010). In a 17.5-year-old mangrove forest, *Avicennia marina* achieved a higher biomass stock than *Rhizophora mucronata* (Kathiresan et al. 2013). Similarly, the AGB of the 'Sonneratia' dominated mangrove site (406 t ha^{-1}) was higher than the 'Rhizophora' dominated site (254 t ha^{-1}), evident from a natural mangrove forest (Kouffman et al. 2011). In BMRF, together only four species, *Avicennia alba*, *Avicennia marina*, *Avicennia officinalis*, and *Sonneratia apetala*, accounted for 85% and 96% of total biomass 'C' in young and old stands, respectively (Fig. 3a). This indicated that *Avicennia* and *Sonneratia* were with high potential for storing live vegetation carbon. The selection of fast-growing tree species increases carbon sequestration and overall carbon stock of mangrove forest (Thant et al. 2012). Thus, prioritizing plantation of high potential, long-term carbon-storing species in mangrove reforestation and afforestation program will increase the overall ecosystem capacity of blue 'C' sinks.

Soil C stock

Mangrove soil is the major C pool and the mean contribution of mangrove soil (at 1 m depth) to total ecosystem carbon stock (TECS) is about 43%, but the share ranges between 11 and 98% (Kauffman et al. 2020). But, we quantified the relative share of only 25% (Fig. 2d), whereas it ranged between 10 and 46% across stands. The estimated mean SOC stock of overall BMRF was $45.89 \pm 1.83 \text{ t C ha}^{-1}$, which was lower than the global average of $369 \pm 6.8 \text{ t C ha}^{-1}$ (Jardine and Siikamäki 2014). Though we had estimated SOC stock at 30 cm depth, our resulting value showed similarity with mangroves of Kerala, at 60 cm soil depth (Harishma et al. 2020) and 100 cm soil depth (Shreelekshmi et al. 2022); Mahanadi delta, at 30 cm soil depth (Sahu et al. 2016); Mekong delta (Nam et al. 2016). The organic 'C' % value of BMRF ranged from 1.06 to 2.42, which was similar to the mangroves of Kerala (Harishma et al. 2020), Mahanadi delta (Sahu et al. 2016), but higher than Sundarban (Mitra et al. 2012). This estimate of soil 'C' % was lower than the global average, especially for estuarine mangroves (7.9%) and Oceanic sites (14.6%) (Donato et al. 2011). The younger forest had relatively lower soil carbon stock than the older forest (Arif et al. 2017). In *Rhizophora apiculata* plantations, the relationship between forest age and total SOC was positive, indicating that carbon continues to be accumulated in soils over time (Ren et al. 2010; Alongi 2011). But, the accumulation rate of SOC stock decreases and saturates in old stands (Ren et al. 2010; Yu et al. 2021). The capacity of carbon sink in plants decreases with stand age, but the soil 'C' accumulation rate remains comparatively constant (Walcker

et al. 2018). In BMRF, the relative contribution of SOC stock to TECS was higher in young stands (i.e., mean: 37%) than in old forest stands (i.e., mean: 17%) (Fig. 3d). This indicates that the SOC stock increases with age of forest stand, while the relative share of soil C stock to TECS decreases in older forest stands. The principal factors that determine soil 'C' stock are BD, 'C' %, soil depth and sampling season (Arif et al. 2017; Mitra et al. 2012). In BMRF, high bulk density, lower soil depth, comparatively sandy soil, and high tide surges possibly play a role in the overall lower soil 'C' concentration.

Total ecosystem carbon stock

The high TECS of mangrove forest is recognized as inevitable in global climate change mitigation policies such as Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) and Nationally Determined Contributions (NDCs) to substantially negate increase in greenhouse gases. New mangrove plantations compensate for natural mangrove loss and the overall ecosystem carbon stocks are increased with stand age, analogous to natural mangroves (Kairo et al. 2008; Ahmed et al. 2023). A study in natural mangrove forest with three stand ages of 15, 45, and 80-year-old stands showed annual accumulation of the ecosystem carbon stocks of 3.61, 3.43 and $2.78 \text{ t ha}^{-1} \text{ year}^{-1}$, respectively (Yu et al. 2021). Thus, the net productivity decreased with stand ages as the major portion of gross primary production was utilized for maintenance (Lele et al. 2021). The TECS of mangrove forest is highly variable and largely attributed to changes in ecosystem conditions such as temperature, rainfall, sedimentation rate, natural disturbances and biotic pressures (Alongi 2014; Hutchison et al. 2014; Friess 2020; Walcker et al. 2018). The TECS of BMRF was found to be lower than the global average due to the under-estimation of the soil 'C' pool (at 30 cm depth) and typically, the soil C stock extends up to several meters (Kauffman et al. 2020). The mean ecosystem $\text{CO}_2 \text{ e}$ of BMRF ($864.71 \pm 100.33 \text{ t CO}_2 \text{ ha}^{-1}$) was higher in mangroves of Kerala state (Sreelekshmi et al. 2022) and Bhitarkanika (Panda et al. 2024). One hectare loss of young and old mangrove stands will lead to the release of 421.17 ± 36.73 and $1160.40 \pm 92.38 \text{ t CO}_2 \text{ e ha}^{-1}$, respectively. Thus, the overall TECS of BMRF of the Subarnarekha estuary (540 ha) was $\sim 0.127 \text{ Mt}$ and $0.467 \text{ Mt CO}_2 \text{ e}$ (FSI 2021).

Correlation among forest attributes

Understanding the existing correlation of forest attributes helps to optimize the true potential of a forest. In mangroves, forest structural attributes such as higher dbh, BA and h contribute towards high stand biomass rather than diversity attributes like richness and H' (Azad et al.

2019). Older mangrove forests having higher BA contributed towards high biomass (Arif et al. 2017; Kamruzzaman et al. 2017; Panda et al. 2024). In planted mangroves, the rate of carbon sequestration had a positive correlation with stand age, tree height, tree diameter, and biomass (i.e., AGB, BGB, and TB) (Kathiresan et al. 2013). In BMRF, trees with significantly higher dbh of *Avicennia* contributed towards high BA (~90%) and TB (~93%) in old natural stands. Less disturbing, structurally complex, and older stands that had high BA and IVI also contributed towards high forest biomass and carbon stock (Ragavan et al. 2021; Panda et al. 2024). The dominance of a particular species is not the strongest determinant in biomass C stock (Harishma et al. 2020). Tree density was a weaker determinant of mangrove biomass than BA, and IVI, especially in young mangrove plantation stands (Fig. 4a–f) and showed similarity with Rahman et al. (2015). However, d was significantly positively correlated with biomass in old natural stands (Fig. 4d, Table 5). When stand ages, d of forest stands decreases as inter- and intraspecies competition increases, leading to lower d , but higher dbh. Soil nitrogen and organic carbon positively help with the increment of tree biomass (Sahu et al. 2016). Soil with high clay content negatively affects the rate of carbon sequestration (Kathiresan et al. 2013). High salinity negatively affects forest variables such as mean h , dbh, BA, biomass compared to the less salinity areas (Ahmad et al. 2023). The soil BD was found to be inversely correlated with soil organic carbon ($r = -0.794$ at $p < 0.01$). A similar trend was seen in Pichavaram mangroves ($r = -0.672$ at $p < 0.01$) (Gnanamoorthy et al. 2019) and mangroves of Kerala (Harishma et al. 2020). Our present findings will be a model study in recognizing stand ages and in the selection of species to optimize mangrove forest carbon stock, a needful step in mitigation of climate adversity.

Limitations

Our result for the overall soil C pool was underestimated as we had collected soil samples only from 30 cm depth, whereas mangrove soils substantially store organic C up to a few meters. The TECS estimated through this study did not include deadwood and litter carbon pool. The effect of regional climate and tropical cyclones on determining the forest structure and biomass of BMRF was not included in this particular study. In addition, river flow, sedimentation dynamics and various human-induced threats to BMRF are yet to be studied.

Conclusions

This study is significant as the BMRF has not yet been documented in any aspects that were characterized through this study. Our results showed that old natural

forest stands stored significantly more biomass C than young planted stands. The correlation analysis figured out how the forest attributes were related to themselves, which could be used to improve the forest complexity and stability of other mangrove forests. Young stands have a high tendency for biomass accumulation and the overall ecosystem carbon stock will increase with stand ages, a nature-based solution to combat reducing atmospheric CO₂. Our results identified the most potential C storage species, such as *Avicennia alba*, *Avicennia marina*, *Avicennia officinalis*, and *Sonneratia apetala*, and suggest their plantation rather than random species selection to further increase the blue C sink potential of BMRF, India. Despite a suitable mangrove habitat, BMRF was found to experience multiple threats such as tree logging, plastic, oil and pesticide pollution, illegal prawn farming, human encroachment, land degradation from tourism development, coastal erosion, tropical cyclones and storm surges, etc. Thus, we suggest participatory incentivization of local people in plantation and conservation activity will not only educate and motivate them to understand the true importance of mangrove forest in their sustenance, but also to combat the global climate crisis.

Abbreviations

AGB	Aboveground biomass
BA	Basal area
BD	Soil bulk density
BGB	Belowground biomass
BMRF	Bichitrapur Mangrove Reserve Forest
CBH	Circumference at breast height
CO ₂ e	CO ₂ equivalents
DBH	Diameter at breast height
EI	Pielou evenness index
GHG	Greenhouse gas
IUCN	International Union for Conservation of Nature and Natural Resources
IVI	Importance value index
RIVI	Relative importance value index
SE	Standard error
SOC	Soil organic carbon
TB	Total biomass
TBC	Total biomass carbon
TECS	Total ecosystem carbon stock

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13717-025-00580-6>.

Supplementary material 1.

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Author contributions

MP, BD and SCS contributed towards conceptualization, and use of methodology. MP and SCS conducted the field study and soil analysis. MP drafted the manuscript. MP and SCS revised the manuscript.

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