ASIAN JOURNAL OF FORESTRY
Volume 6, Number 2, December 2022
Pages: 126-132
E-ISSN: 2580-2844
DOI: 10.13057/asianjfor/r060207

Biomass and carbon accumulation in Northern Bangladesh *Eucalyptus* plantations: Effects of stand structure and age

TANMOY DEY[1,2,♥], MD. AKRAMUL ISLAM[1,2], S. M. RAKIBUL JUBAIR[1]
[1]Research Officer, Bangladesh Forest Research Institute, Ministry of Environment, Forest and Climate Change. Chittagong, Bangladesh.
Tel./fax.: +8801741796384, ♥email: tanmoyfwt100518@gmail.com
[2]Forestry and Wood Technology Discipline, Life science school, Khulna University. Khulna-9208, Bangladesh

Manuscript received: 13 August 2021. Revision accepted: 22 October 2022.

Abstract. *Dey T, Islam MDA, Jubair SMR. 2022. Biomass and carbon accumulation in Northern Bangladesh* Eucalyptus *plantations: Effects of stand structure and age. Asian J For 6: 126-132. Eucalyptus* plantations are a significant carbon sink as a fast-growing species in Bangladesh, but little is known regarding biomass, carbon output, and dynamics with stand age. We, therefore, assessed the stand structure, biomass accumulation, carbon storage, and their changing patterns with age in *Eucalyptus camaldulensis* Dehnh. plantations in the northern part of Bangladesh in early 2021. Biomass and carbon stocks were estimated using the allometric models specific for *E. camaldulensis* from the biophysical tree parameters (i.e., height and DBH). We used the data from 45 sample plots (100 sq. m each) covering different age classes such as 2, 5, 7, 8, 11, 13, and 21 years. The aboveground, belowground, total biomass, and carbon significantly varied between stand ages ($p<0.05$). The highest aboveground, belowground, and total carbon stocks were observed at 21 years, and the lowest was found at two years. We observed a positive and strong relationship between total carbon and stand variables such as stand height, diameter at breast height, basal area, crown width, crown length, and bole height but a negative relationship with density. The mean annual increment of both biomass and carbon increased sharply up to seven years and then decreased. Despite having some ecological constraints, *E. camaldulensis* accumulate a large amount of carbon from the atmosphere, perhaps aiding climate change mitigation.

Keywords: Age, biomass, carbon accumulation, *Eucalyptus camaldulensis,* and stands structure

INTRODUCTION

Carbon dioxide (CO_2) levels in the atmosphere are assumed to have played a substantial role in climate change and come from power generation (38%), transportation (26.56%), building (8.07%), industries (24.76%), and agriculture (1.81%) (Canadell et al. 2007; Yoro and Daramola 2020). The essential strategy for combating climate change is to reduce CO_2 and emissions of other greenhouse gas (IPCC 2001). Through vegetation, forests help mitigate the greenhouse impact by absorbing CO_2 from the atmosphere (Du et al. 2015; Wirabuana et al. 2021). As trees are good carbon sequesters, planted forests (plantations) are regarded as a mitigating tool against the expected rise in atmospheric carbon dioxide concentrations (Sands et al. 1999; Kurz et al. 2009). Also, reduce the impact of natural forest exploitation (negative impacts) (Evans and Turnbull 2004; Kaul et al. 2010; Payn et al. 2015).

In the tropics and subtropics, plantation forestry has focused on a small number of colonizing species with a rapid growth rate, such as *Acacia*, *Eucalyptus*, *Gmelina*, *Pinus*, *Tectona*, and *Populus* (Evans 1992; Harwood and Nambiar 2014). Among these, *Eucalyptus* is well-known for its quick growth, socio-economic and medicinal value, and value as a cash crop due to the availability of wood, particularly for timber and biomass fuel (Dessie and Erkossa 2011; Khan et al. 2020). *Eucalyptus camaldulensis* Dehnh is one of the most common tree species in the village zone of Bangladesh (MoEFCC 2018), meeting a critical demand for residential fuelwood, poles, and posts (Ahmed and Akhter 1995). Plantations in tropical and temperate climates contain significant carbon reserves (Malhi et al. 2008), and fast-growing forest plantations are regarded as very effective carbon sinks that can help reduce the rise in CO_2 levels in the atmosphere (Coleman 2018; Bhattacharya 2019). When plantation forestry is conducted using superior silvicultural techniques, its carbon productivity (Mg ha^{-1} yr^{-1}) exceeds that of natural forests (Lal and Singh, 2000; Baishya et al. 2009). Aboveground carbon stocks have been paid attention for years because they are easy to quantify, either through direct ground observations like field allometric equations or derived results from remote sensing like vegetation index maps (Santantonio et al. 1977; Robinson 2007). Climate, location, land use systems, stand age, plantation structure, and silvicultural methods are the primary determinants of carbon stocks in forest biomass pools (Guo and Gifford 2002; Kaul et al. 2010; Kumar et al. 2016), and generally, plant biomass increases gradually with stand age following long normal distribution (Kumar et al. 2021).

Research of above- and belowground carbon dynamics according to stand age during the normal rotation cycle is essential for a better understanding of the processes that reduced the carbon storage in plantations and recommending effective management of carbon storage. Furthermore, a deeper understanding of these plantations could help with carbon assessments at the regional, national, and global levels due to their importance. Therefore, in this study, we compared total carbon in a *Eucalyptus* plantation at seven stages of development (age 2, 5, 7, 8, 11, 13, and 21 years).

Furthermore, this study would answer the following questions: (i) How do aboveground and belowground biomass and carbon change as a function of stand age (ii) How do above- and belowground biomass and carbon differ depending on their stand structure. Therefore, this study hypothesized that as stand age increased, the biomass and carbon storage of *E. camaldulensis* would show divergent trends and that the contribution of tree biomass to total carbon would rise significantly over time. This study also hypothesized that total carbon has a significant positive relationship with a diameter at 130 cm (DBH), density, basal area, stand height, crown length, crown width, and tree bole height. Inventory data were combined and analyzed to answer the study questions and test the hypotheses. The age-wise contribution to carbon stocks and the relationship between total carbon and stand structure (e.g., mean DBH, density, mean basal area, mean height, mean crown length, mean crown width, and mean bole height). Their variation with age was also evaluated and presented. This study's results might be useful in evaluating potential carbon sequestration in *Eucalyptus* trees and determining appropriate forest management methods to combat climate change.

MATERIALS AND METHODS

Study site

The research was carried out in several sub-districts (Upazilas) under Kurigram District, Bangladesh, which are between 25°.023' and 26°.014' N latitudes and 89°.027 'and 89°.054' E longitudes (Figure 1). The study area includes a humid subtropical climate with a dry winter and a hot summer (Mahmud et al. 2018). The annual temperature ranges from 11.20 to 32.3°C, with an average annual rainfall of 2931 mm (BBS 2013).

Eight plots were established for each age class of 2, 5, 7, and 8; five plots for 11; six for 13 years; and two for 21 years of age, considering the availability of plots in different years. Thus, 45 sample plots (10 m x 10 m) were established, covering a 4,500 m^2 area by a systematic simple random sampling method in *E. camaldulensis* plantation. The trees in the research plots were all given numbers, and the total height (H), diameter at breast height (DBH), crown width (CW), crown length (CL), and bole height (BH) of each tree were measured in March 2021.

Field measurement

Diameter tapes were used to determine the DBH at 1.3 m, and total tree height and bole height were measured with the Haga altimeter. The crown diameter was calculated by taking the arithmetic average of the horizontal crown diameter examined by measuring tape on the north-south and east-west axes. The crown length was calculated by subtracting bole height from the total tree height.

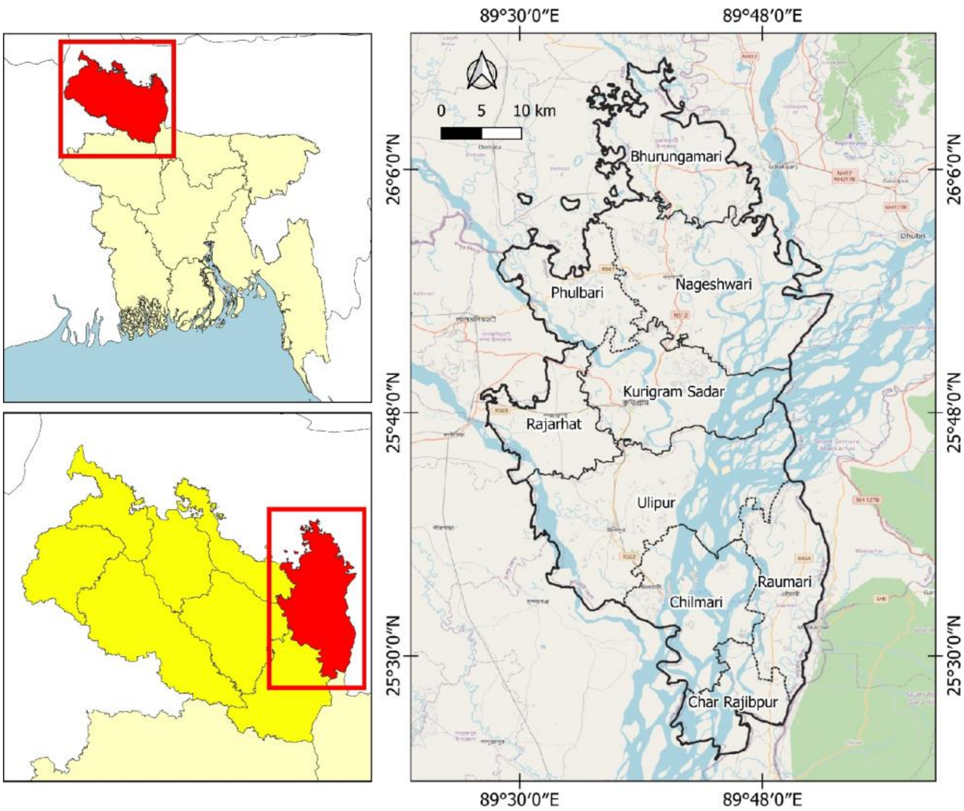

Figure 1. Map of the study area in Kurigram District, Bangladesh

Estimation of biomass and carbon stocks

Each individual's aboveground biomass of *E. camaldulensis* was estimated using allometric relationships between DBH, height, and biomass using a method developed by Hossain et al. (2020).

$$Ln\ (TAGB) = -2.663 + 1.915\ Ln\ (D) + 0.832\ Ln\ (H)$$

Where: TAGB = total aboveground biomass (kg), D = DBH, and H = height

The regression model developed by Cairns et al. (1997) was used to estimate belowground biomass, which depends on information on aboveground biomass.

$$BGB = \exp(-1.0587 + 0.8836 \times \ln AGB)$$

Where: AGB denotes aboveground biomass, and BGB denotes belowground biomass

The following formula calculates the Mean Annual Increment (MAI) of biomass:

MAI of biomass = (Total biomass) /age (years)

A conversion factor of 0.47 was used to quantify carbon stocks as suggested by the IPCC (2006),

Carbon = biomass × 0.47

All the biomass and carbon were expressed as Mg ha^{-1}

Statistical analysis

Before the ANOVA test, the normality and homogeneity of variance assumptions were met. Then, the variations in biomass and carbon stocks, as well as stand age, were studied using a one-way analysis of variance (ANOVA). Additionally, after a significant difference was observed, pairwise comparisons were made using post hoc testing (Tukey's HSD). Finally, the relationship between biomass stocks and stand structural factors was also tested using correlation regression. A significance value of $p < 0.05$ was used for all statistical studies to display the results. The R version 3.1.5 (R Core Team 2017) was used for all statistical analyses and figures.

RESULTS AND DISCUSSION

Data from seven age classes (i.e., 2, 5, 7, 8, 11, 13, and 21 years) of *E. camaldulensis* showed differences in structural variables such as mean density, basal area, height, DBH, bole height, crown length, and crown width. The lowest basal area, height, DBH, bole height, crown length, and crown width are 0.8 ± 0.0 $m^2\ ha^{-1}$, 4.7 ± 0.2 m, 2.0 ± 0.1 cm, 3.2 ± 0.2 m, 1.5 ± 0.2 m and 1.8 ± 0.5m, respectively, without mean density 1637± 302 tree ha^{-1} which is the highest in two years of plantation (Table 1). On the other hand, the highest basal area, height, DBH, bole height, crown length, and crown width are 5.8 ± 0.1 $m^2\ ha^{-1}$, 30.9 ± 0.9 m, 42.7 ± 0.1 cm, 14.9 ± 0.7 m, 16.1 ± 0.2 m and 7.6 ± 0.4 m respectively, without mean density 400 ± 0 n ha^{-1} which is the lowest in 21 years of plantation (Table 1).

Aboveground and belowground biomass (Mg ha^{-1}) increased significantly with stand age, with the highest and lowest above and belowground biomass found at 21 and 2 years of age, respectively. Similarly, above and belowground carbon (Mg C ha^{-1}) increased with stand age, with the highest and lowest above and belowground carbon found at 21 and 2 years of age, respectively (Figure 2).

The current study observed a strong positive relationship between total carbon (Mg C ha^{-1}) with mean DBH (R^2=0.94, p<2.2e-16) and mean height (R^2=0.90, p<2.2e-16). In the meantime, this study also observed a strong positive relationship of total carbon (Mg C ha^{-1}) with the mean basal area (R^2=0.76, p<8.6e-15), mean crown width (R^2=0.84, p<2.2e-16), mean crown length (R^2=0.8, p<2.2e-16) and mean bole height (R^2=0.79, p<2.2e-16) but a negative relationship with density (R^2=0.75, p<1.3e-14) (Figure 3).

The highest aboveground carbon (302.6 ± 10.9 Mg C ha^{-1}) and belowground carbon (49.4 ± 1.6 Mg C ha^{-1}) were found for 21 year's age *Eucalyptus* plantation (Figure 2, Table 2). On the other hand, the lowest aboveground (0.8 ± 0.2 Mg C ha^{-1}) and belowground carbon (0.3 ± 0.1 Mg C ha^{-1}) were found for two years of age *Eucalyptus* plantation. The mean above and belowground carbon of all age classes is (145.8 ± 8.3 Mg C ha^{-1}) and (25.1 ± 1.3 Mg C ha^{-1}), respectively (Table 2). The mean increment of *E. camaldulensis* increases sharply at a young age (i.e., up to seven years) and decreases (at eight years). Again, the increasing trend observed up to 11 years afterward decreased sharply to 21 years (Figure 4).

Table 1. Stand structure of different age *Eucalyptus* plantation

Age	Density (n ha^{-1})	Basal area ($m^2\ ha^{-1}$)	Height (m)	DBH (cm)	Bole height (m)	Crown length (m)	Crown width (m)
2	1637± 302	0.8 ± 0.0	4.7 ± 0.2	2.0 ± 0.1	3.2 ± 0.2	1.5 ± 0.2	1.8 ± 0.5
5	1438± 168	1.7 ± 0.3	10.6 ± 0.4	11.9 ±0.5	7.1 ± 0.6	3.4 ± 0.4	3.6 ± 0.1
7	1412 ± 180	4.5 ± 0.3	11.9 ± 0.9	19.8 ± 0.8	7.5 ± 0.5	4.4 ± 0.4	3.1 ± 0.8
8	1187 ± 64	4.7 ± 0.3	12.8 ± 0.4	22.3 ± 0.7	7.6 ± 0.5	5.2 ± 0.5	3.5 ± 0.9
11	800 ± 70	4.6 ± 0.5	24.8 ± 1.0	26.9 ± 1.1	17.5 ± 0.8	7.3 ± 1.1	5.2 ± 0.6
13	716 ± 75	4.6 ± 0.3	27.6 ± 1.6	28.5 ± 0.8	18.9 ± 1.4	8.7 ± 1.9	4.5 ± 0.4
21	400 ± 0	5.8 ± 0.1	30.9 ± 0.9	42.7 ± 0.1	14.9 ± 0.7	16.1 ± 0.2	7.6 ± 0.4

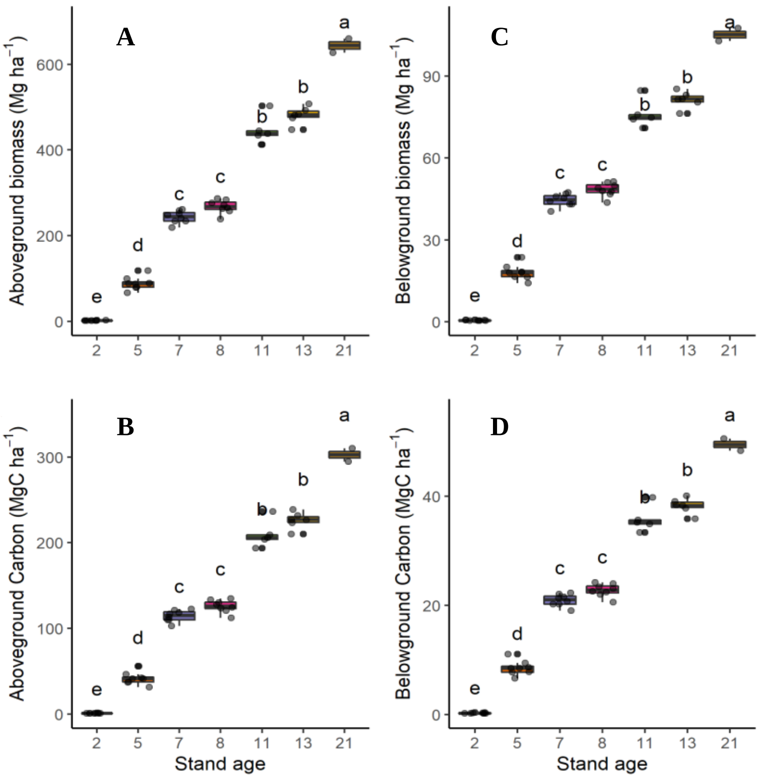

Figure 2. Boxplots showing changes in above and belowground biomass and carbon with stand age in a *Eucalyptus* plantation: A. Aboveground biomass, B. Aboveground carbon, C. Belowground biomass, D. Belowground carbon. The Tukey-HSD post hoc test, which was adjusted from one-way ANOVA, is indicated by different letters on the top of the boxes

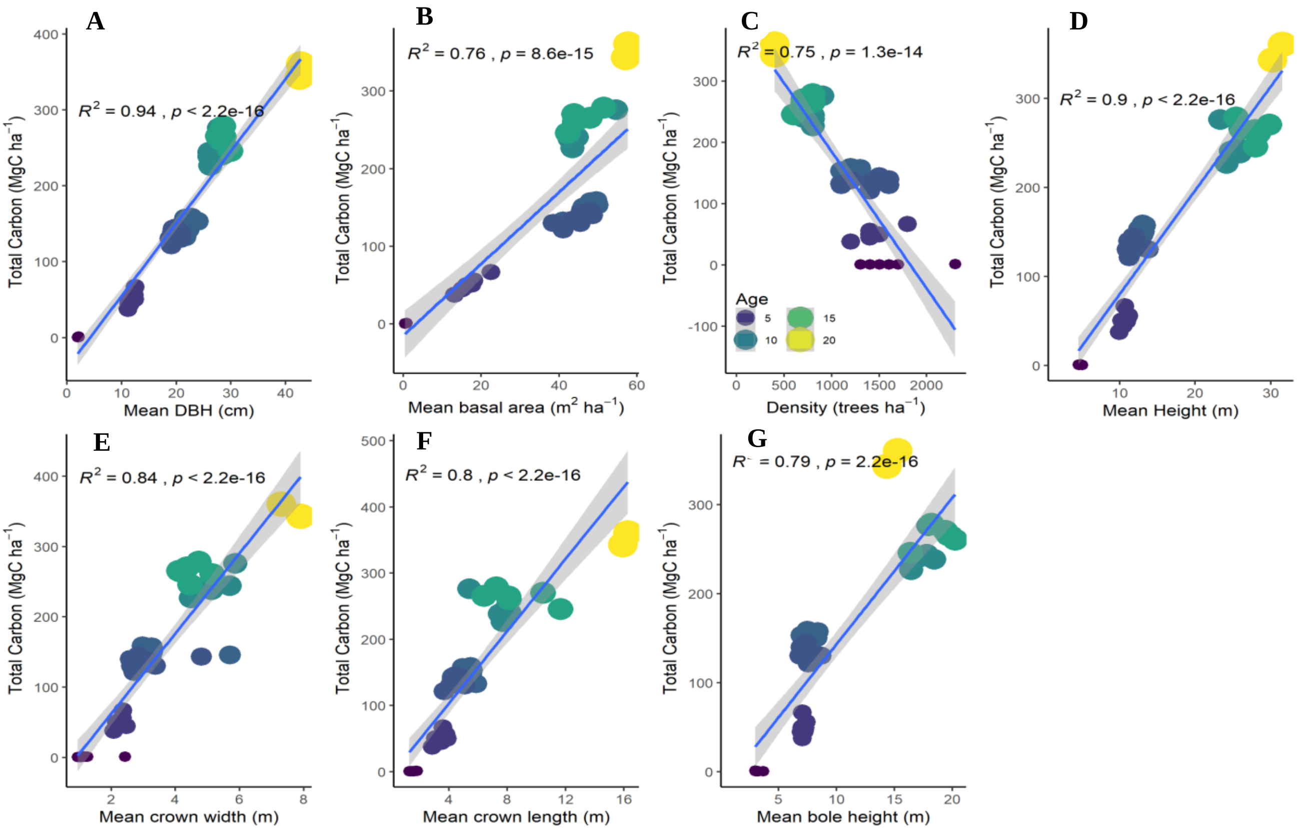

Figure 3. The relationships between estimated total carbon stocks in *Eucalyptus* plantation and stand structural attributes: A. Diameter at breast height (DBH), B. Basal area, C. Stand density, D. Tree height, E. Crown width, F. Crown length, G. Bole height. The larger the points, the older the stands

Table 2. Biomass (Mg ha^{-1}) and carbon stocks (Mg C ha^{-1}) of different age *Eucalyptus* plantation

Age (years)	Aboveground biomass (carbon)	Belowground biomass (carbon)	Total biomass (carbon)
21	643 ± 23.2 (302.6 ± 10.9)	105 ± 3.3 (49.4 ± 1.6)	748 ± 26.5 (352 ± 12.5)
13	481 ± 20.1 (226.1 ± 9.5)	81 ± 3.0 (38.2 ± 1.4)	562 ± 23.1 (264.3 ± 10.9)
11	446 ± 34.1 (209.7 ± 16.5)	76 ± 5.1 (35.7 ± 2.4)	522 ± 39.2 (245.4 ± 18.9)
8	267 ± 15.6 (125.8 ± 7.3)	48 ± 2.5 (22.7 ± 1.2)	315 ± 18.1 (148.5 ± 8.5)
7	243 ± 14.2 (114.3 ± 6.7)	44 ± 2.3 (20.9 ± 1.0)	287 ± 16.5 (135.2 ± 7.7)
5	88 ± 15.4 (41.5 ± 7.3)	18 ± 2.8 (8.5 ± 1.3)	106 ± 18.2 (50 ± 8.6)
2	1.7 ± 0.4 (0.8 ± 0.2)	0.5 ± 0.1 (0.3 ± 0.1)	2.2 ± 0.5 (1.1 ± 0.3)
Mean	309 ± 17.5 (145.8 ± 8.3)	53 ± 2.7 (25.1 ± 1.3)	363 ± 20.3 (170.9 ± 9.6)

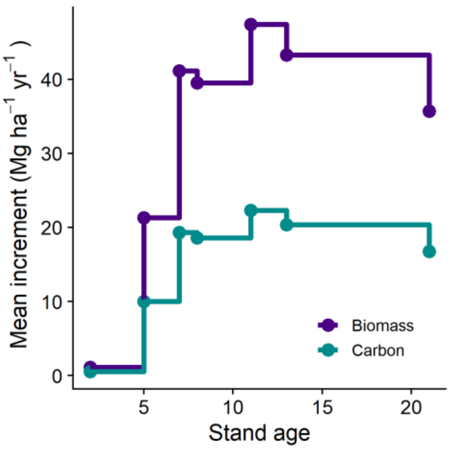

Figure 4. Visualizes the mean biomass and carbon increment in *Eucalyptus* plantations by stand ages

Discussion

This study reveals that above- and belowground biomass and carbon varied with stand age (Table 2), which supports the previous hypothesis. Because *Eucalyptus* is a rapidly growing species, there is a significant difference in above and belowground carbon and biomass with age (Figure 2). Therefore, the total carbon and biomass are greater in the 21-year *Eucalyptus* plantation following 13, 11, 8, 7, 5, and 2 years. Zhang et al. (2012) found a similar result: the total biomass and carbon production of *E. camaldulensis* vary with age. Zhang et al. (2018) found that middle-aged and mature *Eucalyptus* plantations produced considerably more total biomass carbon than younger ones ($P < 0.01$). Du et al. (2015) found the amount of carbon stored in tree biomass increased as the forest became older, from 3.1 Mg ha^{-1} at age 1 to 24.0, 31.6, 42.6, and 70.1 Mg ha^{-1} at ages 2, 3, 4-5, and 6-8 years, respectively. Ulman and Avudainayagam (2014) discovered that total biomass carbon content ranged from 10.25 t ha^{-1} (one-year plantation) to 82.16 t ha^{-1} (four-year plantation) for *Eucalyptus tereticornis* Sm. in the Forest College and Research Institute at Mettupalayam in India. According to Joshi et al. (2013), carbon sequestration by an 8-year *Eucalyptus* hybrid plantation in the Terai region of the central Himalayas was 7.88 t Cha^{-1} per year. Ram et al. (2011) found *E. tereticornis* clones planted in a strip pattern in a water logging site in Haryana stored 15.5 t ha^{-1} of carbon at the 5-year 4 months old plantation. According to Kumar et al. (2021), the total carbon stock (plant + soil) in an 8-year plantation of *E. tereticornis* ranged from 114.1 to 118.8 Mg C ha^{-1} in semi-arid regions of Northwest India.

On the other hand, total carbon has a strong positive relationship by stand structural parameters such as height, DBH, basal area, crown height, crown length, and bole height but a negative relationship with density (Figure 3), which supports the second hypothesis. This positive relationship (without stand density) was because more height, basal area, DBH, crown height, crown length, and bole height indicate greater biomass. Therefore, more biomass indicates more carbon stock. Chave et al. (2005) stated that DBH, height, and canopy spread closely correlate to biomass. Total aboveground biomass is very strongly related ($R^2 = 0.99$) to DBH (Kuyah et al. 2012) and tree volume (Henry et al. 2009). Wider spacing provided enough space and less competition for higher biomass accumulation, which explains the negative relationship between density and total carbon stock (Kumar et al. 2021). However, Jaman et al. (2016) found that the stem density ($R^2 = 0.258$) and DBH ($R^2 = 0.182$) of tree species had no strong relationship with carbon stock at the home garden in the Rangpur District of Bangladesh. Chauhan et al. (2009) found that in an *E. tereticornis* plantation, tree stem C storage (4.20 t ha^{-1}) and total C storage (9.36 t ha^{-1}) in Punjab, India.

Biswas and Hasan (2020) found aboveground biomass and carbon at 116.397 Mgha^{-1} and 58.199 Mgha^{-1} for *E. citriodora* at a roadside agroforestry plantation in Sadar Upazila, Mymensingh district, Bangladesh. They also found a strong relationship between basal area and aboveground carbon stock ($R^2 = 0.874$, p-value<0.05). Also a very strong relationship between stand density ha^{-1} and total aboveground carbon stock ($R^2 = 0.997$, p-value<0.05) for 23 species, including *E. citriodora*. This different result could be due to limited resources like water and nutrients in our study area (Tamang et al. 2021) and monoculture *Eucalyptus* plantation. Stands accumulated biomass quickly as they grew older, well above the rate of accumulation observed in other tropical and subtropical plantation studies (Singh and Toky 1995; Bauhus et al. 2004; Zewdie et al. 2009).

The reason for the variation of total biomass and carbon in *Eucalyptus* species is not only the variation of age but also due to their rapid growth; the case of *Eucalyptus* trees form a forest with low-biomass density (Zhang et al. 2012). Climate factors, particularly temperature and water availability, impact potential forest biomass output and carbon density on a global and regional scale (Lieth 1975). The rising temperature and decreasing precipitation greatly influence forest vegetation's structure, functions, dynamics, and distribution. These changes would affect the forest vegetation's carbon sequestration potential (CSP) (Hui et al. 2017; Zhou et al. 2022). Site condition and soil characteristics are important at the local level for preserving the quality of the water and sustaining long-term site production, and soil properties are significantly influenced by the age of the plantation (Omoro et al. 2013; Tamang et al. 2021; Schoonover and Crim 2015). Moreover, organic matter quality, which is related to species, and thus forest type, soil type, and texture are important aspects, too (Jobbágy and Jackson 2000). However, to a greater or lesser extent, human activities and management identify the true biomass and carbon density (Brown and Gaston 1995). The mean increment ($Mgha^{-1}yr^{-1}$) of *E. camaldulensis* increases sharply up to seven years, then decreases in years eight and nine, but again increases up to 11 years, then sharply decreases up to 13 years, and gently decreases up to 21 years (Figure 4). According to Kumar et al. (2021), annual growth in tree height, DBH, biomass, and carbon storage of *E. tereticornis* was high for the first six years before slowing down for the next eight years, which is nearly similar to these findings. Furthermore, Ram et al. (2011) and Kumar et al. (2016) observed a striking similarity in the growth and biomass of *E. tereticornis* and *Populus deltoides* in plantation forestry in North-Western India. Shin et al. (2007) found the highest net mean annual increment (MAI) in carbon stock at 9.83 (SE 1.50) t $Cha^{-1}yr^{-1}$ in the *E. camaldulensis* stands, followed by *A. mangium* (7.48 t C $ha^{-1}yr^{-1}$, SE 0.66) and the lowest was in the *Gmelina arborea*, at 0.25 t C $ha^{-1}yr^{-1}$ (SE 0.64) in Bangladesh. Du et al. (2015) found that annual rates of biomass carbon accumulation in trees in the *Eucalyptus* stand were 3.1, 20.9, 7.6, 5.0, and 9.2 Mg ha^{-1} y^{-1} for ages 1, 2, 3, 4-5, and 6-7 years, respectively. Shin et al. (2007) stated that the largest net increment (10 t $ha^{-1}year^{-1}$) was found in 8-year-old *Acacia auriculiformis* A.Cunn. Ex Benth. and 8-year-old *E. camaldulensis*, followed by 18-year-old *E. camaldulensis*, while the lowest was reported in the *G. arborea* plantation among 13 plantation species in the hilly area of Bangladesh. Several variables, including planting material, density, growth circumstances, site attributes, age, structure, and, most crucially, management strategies, influences the total biomass output from a plantation (Goswami et al. 2014). The Mean height, DBH of the lowest age (2 years old) *Eucalyptus* tree is 4.7 ± 0.2 m, 2.0 ± 0.1 cm, and the mean height, DBH of the highest age (21 years old) is 30.9 ± 0.9 m, 42.7 ± 0.1 cm respectively (Table 1). Dogra (2011) found carbon sequestration rates of 236.8 kg per tree at height and a DBH of 24 m and 30 cm, respectively, for *E. tereticornis* in India. *E. camaldulensis* can reach up to 20 m tall and rarely exceeds 40 m; if properly managed, this species will be highly economical (Hassan 1994).

In conclusion, this research reveals that *Eucalyptus* is a fast-growing forest tree with significant potential for biomass and carbon sequestration. This study also found that biomass and carbon of *Eucalyptus* plantations increase with stand age. A positive and strong relationship exists between total carbon and structural attributes such as stand height, DBH, basal area, density, crown width, crown length, and bole height. Low-density stands of *E. camaldulensis* accumulate more biomass and carbon than high-density stands. This study only examines the biomass and carbon productivity changes in *Eucalyptus* plantations as a function of stand structure and stand age. Still, possible responsible factors for this were not observed. Thus, future research could be interesting by covering broad geographical ranges and highlighting the soil variables.

REFERENCES

Ahmed FU, Akhter S. 1995. Problems and prospects of *Eucalyptus*. In: Amin SMR, Ali MO, Fattah MIM (eds). *Eucalyptus* in Bangladesh, Proceedings of the National Seminar held at Bangladesh Agricultural Research Council, Dhaka on 16 April, 1994.

Baishya R, Barik SK, Upadhaya K. 2009. Distribution pattern of aboveground biomass in natural and plantation forests of humid tropics in Northeast India. Trop Ecol 50: 295-304.

Bangladesh Bureau of Statistics (BBS). 2013. District Statistics 2011: Kurigram. P-3. www.bbs.gov.bd.

Bauhus J, Van Winden AP, Nicotra AB. 2004. Aboveground interactions and productivity in mixed-species plantations of *Acacia mearnsii* and *Eucalyptus globulus*. Can J For Res 34: 686-694. DOI: 10.1139/x03-243.

Bhattacharya A. 2019. Global Climate Change and Its Impact on Agriculture. Changing Climate and Resource Use Efficiency in Plants. Chapter 1, Academic Press, Cambridge. DOI: 10.1016/ B978-0-12-816209-5.00001-5.

Biswas M, Hasan M. 2020. Measurement of aboveground carbon stocks of roadside agroforestry plantation at Sadar Upazila of Mymensingh District in Bangladesh. J Bangladesh Agril Univ 18 (2): 214-221. DOI: 10.5455/jbau.91198.

Brown S, Gaston G. 1995. Use of forest inventories and geographic information systems to estimate biomass density of tropical forests: Applications to Tropical Africa. Environ Monit Assess 38: 157-168. DOI: 10.1007/BF00546760.

Cairns MA, Brown S, Helmer EH, Baumgardner GA. 1997. Root biomass allocation in the world's upland forests. Oecologia 111: 1-11. DOI: 10.1007/s004420050201.

Canadell JG, le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway RJ, Gillett NP, Houghton RA, Marland G. 2007. Contributions to accelerating atmospheric CO^2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc Natl Acad Sci 104: 18866-18870. DOI: 10.1073/pnas.0702737104.

Chauhan SK, Gupta N, Ritu S, Chauhan R. 2009. Biomass and carbon allocation in different parts of agroforestry tree species. Indian For 135 (7): 981-993.

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Folster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riera B, Yamakura T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145 (1): 78-99. DOI: 10.1007/s00442-005-0100-x.

Coleman A. 2018. Forest-based carbon sequestration, and the role of forward, futures, and carbon-lending markets: A comparative institutions approach. J Forest Econ 33: 95-104. DOI: 10.1016/ j.jfe.2018.12.002.

Dessie G, Erkossa T. 2011. Eucalyptus in East Africa. In: Socio-economic and environmental issues. May. p. 42, Working paper FP46/E. FAO, Rome, Italy.

Dogra AS. 2011. Contribution of trees outside forests toward wood production and environmental amelioration. Indian J Ecol 38: 388-400.

Du H, Zeng F, Peng W, Wang K, Zhang H, Liu L, Song T. 2015. Carbon storage in a *Eucalyptus* plantation chronosequence in Southern China. Forests 6 (6): 1763-1778. DOI: 10.3390/f6061763.

Evans J, Turnbull JW. 2004. Plantation Forestry in the Tropics: The role, Silviculture and Use of Planted Forests for Industrial, Social, Environmental, and Agroforestry Purposes. 3rd Edn. Oxford University Press, Oxford.

Evans J. 1992. Plantation Forestry in Tropics. 2nd ed. Clarendon Press, Oxford.

Goswami S, Verma KS, Kaushal R. 2014. Biomass and C sequestration in different agroforestry systems of a Western Himalayan watershed. Biol Agric Hortic 30 (2): 88-96. DOI: 10.1080/01448765.2013.855990.

Guo LB, Gifford M. 2002. Soil carbon stocks and land use: A meta analysis. Glob Change Biol 8: 345-360. DOI: 10.1046/j.1354-1013.2002.00486.x.

Harwood CE, Nambiar EKS. 2014. Sustainable Plantation Forestry in South-East Asia. ACIAR Technical Reports No. 84. Australian Centre for International Agricultural Research, Canberra.

Hassan MM. 1994. Prospect of *Eucalyptus* in Bangladesh. Bangladesh J For Sci 23 (1): 12-19.

Henry M, Tittonell P, Manlay RJ, Bemoux M, Albrecht A, Vanlauwe B. 2009. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agric Ecosyst Environ 129 (1-3): 238-252. DOI: 10.1016/j.agee.2008.09.006.

Hossain M, Siddique MRH, Abdullah SMR, Saha C, Islam SMZ, Iqbal MZ, Akhter M. 2020. Development and evaluation of species-specific biomass models for most common timber and fuelwood species of Bangladesh. Open J For 10 (01): 172-185. DOI: 10.4236/ojf.2020.101012.

Hui F, Deng Q, Tian HQ, Luo YQ. 2017. Climate change and carbon sequestration in forest ecosystems. In Handbook of Climate Change Mitigation and Adaptation. Springer International Publishing, New York, USA. DOI: 10.1007/978-3-319-14409-2_13.

IPCC (Climate Change). 2001. The Scientific Basis. Cambridge University Press, Cambridge, UK.

IPCC. 2006. Guidelines for National Greenhouse Gas Inventories, Agriculture, Forestry and Other Land Use (AFLOLU). Institute for Global Environmental strategies, Hayama, Japan.

Jaman MS, Hossain MF, Islam MH, Helal MGJ, Jamil M, Rahman MM. 2016. Quantification of carbon stock and tree diversity of homegardens in Rangpur District, Bangladesh. Intl J Agric For 6 (5): 169-180. DOI: 10.5923/j.ijaf.20160605.01.

Jobbágy EJ, Jackson RB. 2000. The vertical distribution of soil organic carbon and its relation to climate change and vegetation. Ecol Appl 10 (2): 423-436. DOI: 10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2.

Joshi NR, Tewari A, Singh V. 2013. Biomass and carbon accumulation potential towards climate change mitigation by young plantations of *Dalbergia sissoo* Roxb. and *Eucalyptus* hybrid in Terai Central Himalaya, India. Am J Res Commun 1 (4): 261-274.

Kaul M, Mohren GMJ, Dadhwal VK. 2010. Carbon storage and sequestration potential of selected tree species in India. Mitig Adapt Strateg Glob Chang 15: 489-510. DOI: 10.1007/s11027-010-9230-5.

Khan N, Fahad S, Faisal S, Akbar A, Naushad M. 2020. Socio-economic and medicinal review of *Eucalyptus* tree in the world. SSRN Elect J 1-41. DOI: 10.2139/ssrn.3644215.

Kumar P, Mishra AK, Chaudhari SK, Sharma DK, Rai AK, Singh K, Rai P, Singh R. 2021. Carbon sequestration and soil carbon build-up under *Eucalyptus* plantation in semi-arid regions of Northwest India. J Sustain For 40 (4): 319-331. DOI: 10.1080/10549811.2020.1749856.

Kumar P, Mishra AK, Chaudhari SK, Singh R, Singh K, Rai P, Pandey CB, Sharma DK. 2016. Biomass estimation and carbon sequestration in Populus deltoides plantations in India. J Soil Salin Water Qual 8 (1): 25-29.

Kurz WA, Dymond CC, White TM, Stinson G, Shaw CH, Rampley GJ, Smyth C, Simpson BN, Neilson ET, Trofymow JA, Metsaranta J, Apps MJ. 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol Model 220: 480-504. DOI: 10.1016/j.ecolmodel.2008.10.018.

Kuyah S, Dietz J, Muthuri C, Jamnadass R, Mwangi P, Coe R, Neufeldt H. 2012. Allometric equations for estimating biomass in an agricultural landscape: I. aboveground biomass. Agric Ecosyst Environ 140 (1): 430-440. DOI: 10.1016/j.agee.2012.05.011.

Lal M, Singh R. 2000. Carbon sequestration potential of Indian forests. Environ Monit Assess 60: 315-327. DOI: 10.1023/A:1006139418804.

Lieth H. 1975. Modeling the primary productivity of the world. In: Lieth H, Whittaker RH (Eds). Primary Productivity of the Biosphere. Springer-Verlag, New York. DOI: 10.1007/978-3-642-80913-2.

Mahmud KH, Abid SB, Ahmed R. 2018. Development of a climate classification map for Bangladesh based on Koppen's climatic classification. Soc Sci 39: 23-36.

Malhi Y, Roberts JT, Betts RA, Killeen TJ, Li W, Nobre CA. 2008. Climate change, deforestation, and the fate of the Amazon. Science 319 (5860): 169-172. DOI: 10.1126/science.1146961.

MoEFCC. 2018. The Submission of Bangladesh's Forest Reference Level for REDD+ under the UNFCCC, Ministry of Environment, Forest and Climate Change (MoEFCC), Government of Bangladesh, Dhaka, Bangladesh. Available online: https://redd.unfccc.int/files/2019.

Omoro LMA, Starr M, Pellikka PKE. 2013. Tree biomass and soil carbon stocks in indigenous forests in comparison to plantations of exotic species in the Taita Hills of Kenya. Silva Fennica 47 (2): 1-18. DOI: 10.14214/sf.935.

Payn T, Carnus JM, Freer-Smith P, Kimberley M, Kollert W, Liu S, Orazio C, Rodriguez L, Silva LN, Wingfield MJ. 2015. Changes in planted forests and future global implications. For Ecol Manag 352: 57-67. DOI: 10.1016/j.foreco.2015.06.021.

Ram J, Dagar JC, Lal K, Singh G, Toky V, Tanwar VS, Dar SR, Chauhan MK. 2011. Biodrainage to combat waterlogging, increase farm productivity and sequester carbon in canal command areas of northwest India. Curr Sci 100 (11): 1673-1680.

Robinson D. 2007. Implications of a large global root biomass for carbon sink estimates and for soil carbon dynamics Proc Royal Soc B: Biol Sci 274: 2753-2759. DOI: 10.1098/rspb.2007.1012.

Sands PJ, Rawlins W, Battaglia M. 1999. Use of a single plantation productivity model to study the proftability of irrigated *Eucalyptus globulus*. Ecol Model 117: 125-141. DOI: 10.1016/S0304-3800(99)00021-6.

Santantonio D, Herman RK, Overtos WS. 1977. Root biomass studies in forest ecosystems. Pedobiologia 17: 1-31.

Schoonover JE, Crim JF. 2015. An Introduction to soil concepts and the role of soils in watershed management. J Contemp Water Res Educ 154 (1): 21-47. DOI: 10.1111/j.1936-704x.2015.03186.x.

Shin MY, Miah MD, Lee KH. 2007. Potential contribution of the forestry sector in Bangladesh to carbon sequestration. J Environ Manag 82 (2): 260-276. DOI: 10.1016/j.jenvman.2005.12.025.

Singh V, Toky OP. 1995. Biomass and net primary productivity in Leucaena, Acacia and Eucalyptus, short rotation, high density ('energy') plantations in arid India. J Arid Environ 31: 301-309. DOI: 10.1016/S0140-1963(05)80034-5.

Tamang M, Chettri R, Vineeta, Shukla G, Bhat JA, Kumar A, Kumar M, Suryawanshi A, Cabral-Pinto M, Chakravarty S. 2021. Stand structure, biomass and carbon storage in Gmelina arborea plantation at agricultural landscape in foothills of Eastern Himalayas. Land 10 (4): 1-15. DOI: 10.3390/land10040387.

Ulman Y, Avudainayagam S. 2014. Carbon storage potential of *Eucalyptus tereticornis* plantations. Indian For 140 (1): 53-58.

Wirabuana PYAP, Alam S, Matatula J, Harahap MM, Nugroho Y, Idris F, Meinata A, Sekar DA. 2021. The growth, aboveground biomass, crown development, and leaf characteristics of three *Eucalyptus* species at initial stage of planting in Jepara, Indonesia. Biodiversitas 22: 2859-2869. DOI: 10.13057/biodiv/d220550.

Yoro KO, Daramola MO. 2020. CO_2 emission sources, greenhouse gases, and the global warming effect. In Advances in Carbon Capture (Issue August). Elsevier Inc. DOI: 10.1016/b978-0-12-819657-1.00001-3.

Zewdie M, Olsson M, Verwijst T. 2009. Aboveground biomass production and allometric relations of *Eucalyptus globulus* Labill. coppice plantations along a chronosequence in the central highlands of Ethiopia. Biomass Bioenerg 33: 421-428. DOI: 10.1016/j.biombioe.2008.08.007.

Zhang H, Duan HB, Song MW, Guan DS. 2018. The dynamics of carbon accumulation in *Eucalyptus* and *Acacia* plantations in the Pearl River delta region. Ann For Sci 75: 40. DOI: 10.1007/s13595-018-0717-7.

Zhang H, Guan D, Song M. 2012. Biomass and carbon storage of *Eucalyptus* and *Acacia* plantations in the Pearl River Delta, South China. For Ecol Manag 277: 90-97. DOI: 10.1016/j.foreco.2012.04.016.

Zhou R, Zhang Y, Peng M, Jin Y, Song Q. 2022. Effects of climate change on the carbon sequestration potential of forest vegetation in Yunnan Province, Southwest China. Forests 13 (2): 1-12. DOI: 10.3390/f13020306.