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Biomass accumulation and carbon sequestration potential in varying tree species, ages and densities in Gunung Bromo Education Forest, Central Java, Indonesia

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Abstract. *Darmawan AA, Ariyanto DP, Basuki TM, Syamsiyah J, Dewi WS. 2022. Biomass accumulation and carbon sequestration potential in varying tree species, ages and densities in Gunung Bromo Education Forest, Central Java, Indonesia. Biodiversitas 23: 5093-5100.* Forest biomass plays an important role in carbon storage to mitigate climate change. While many studies have investigated the carbon stock of various forests, adding knowledge in the context of education forest might enrich the importance of this forest as a carbon pool besides its role for education purposes. Gunung Bromo Education Forest in Karanganyar District, Central Java, Indonesia consists of several tree cover types with each type having a different ability to absorb carbon dioxide in the atmosphere. This research aimed to determine the accumulation of biomass in Gunung Bromo Education Forest and to investigate the potential for carbon sequestration across different tree species, age classes and densities. Three species of tree (i.e. pine, Indonesian rosewood and mahogany) with varying ages were measured and calculated the biomass (i.e. tree, litter and understorey) and total carbon sequestration potentials (i.e. tree, litter and understorey, and soil organic carbon). This study used purposive sampling method across 9 combinations of tree cover type and age classes, each with 3 replication, resulting in a total of 27 sampling points. The results showed pine stands planted in 1973 had the highest tree biomass of 461.08 t ha^{-1} and while the pine agroforest planted in 2016 and Indonesian rosewood agroforest planted in 2018 had the lowest tree biomass with 1.02 t ha^{-1} and 0.39 t ha^{-1}, respectively. Similarly, the pine stands planted in 1973 had the highest total carbon sequestration of 372.68 t ha^{-1} and the lowest in the pine agroforest planted in 2016 and Indonesian rosewood agroforest planted in 2018 with 187.11 t ha^{-1} and 193.58 t ha^{-1} respectively. The results of this study strengthen the common agreement in previous carbon studies that tree age strongly affects biomass accumulation and carbon sequestration, in which the older the plant, the higher the carbon sequestration potential than that of younger plants.

Keywords: Age class, biomass accumulation, carbon sequestration, forest, tree density

INTRODUCTION

Future climate change scenarios predict a temperature increase of 0.4-2.0ºC in 2030 and 1.0-6.0ºC in 2070 (McKenney et al. 2013; Ospina-Noreña et al. 2019; Santiz et al. 2016; Saputra and Lee 2021). In the long run, this condition could impact ecosystems on the Earth, threatening humans and other living organisms. The warming climate is mainly caused by the increase in atmospheric concentrations of greenhouse gases, one of which is carbon dioxide or CO_2 (IPCC, 2014; Nunes et al. 2019). Therefore, a key aspect of mitigating the increase of global temperature is by reducing the concentration of CO_2 through carbon sequestration (Grassi et al. 2017). Forest is among the largest carbon pools on Earth which also provides various benefits for life (Chanlabut and Nahok 2022; McKenney et al. 2013; Robinson et al. 2013; Solomon et al. 2015).

Forests have various ecosystem services, including the provision of materials (e.g. timber, non-timber products) to fulfill human needs, water regulation, soil conservation, carbon sequestration, habitat of biodiversity and socio-cultural benefits (e.g. traditional uses, ecotourism) (Fee 2019). Such ecosystem services are more prominent in the tropical region since tropical rainforests host a great level of biodiversity as well as store a large amount of carbon (Khaine and Woo 2015; McAlpine et al. 2018; Weiskopf et al. 2020; Hakkenberg and Goetz 2021). Indonesia is among the countries with the largest tropical forest in the world, which plays an active role in climate change mitigation by preserving its forest as carbon pools (Basuki et al. 2022).

There are several studies on the theme of forest biomass with various land cover types (Li et al. 2021; Moreira and Pires 2016). Such studies showed that each land cover type and management activity has a different ability to absorb carbon dioxide in the atmosphere and sequester carbon in the form of living biomass. The management intensity of crops also affects the carbon sequestration capacity (Yin et al. 2012). For example, low biomass occurs on agroforestry lands when there is tree-cutting activities (Hanberry et al. 2016; Silva et al. 2020). In addition, biomass is affected by the tree stand density, which is closely related to the surrounding environmental conditions, both biotic and abiotic factors (Bayat et al. 2021; Oliver and Morecroft 2014; Teshome et al. 2020). The age of the stand also affects the biomass and the amount of carbon stored in a stand (González-García et al. 2013). The rate of biomass accumulation of the stand will continue to increase until a certain age and reach its peak before it decreases as the stand is over-maturity (Dey et al. 2019).

Gunung Bromo Education Forest is a state forest for special purpose (*Kawasan Hutan dengan Tujuan Khusus*/KHDTK). It is located in Karanganyar District, Central Java Province, Indonesia with an area of 126.29 ha. It was originally a limited production forest area under the management of Perum Perhutani Regional Division of Central Java and since April 2018, the Gunung Bromo Education Forest has been designated as an education and research forest under the management of Sebelas Maret University based on the Decree of the Minister of Environment and Forestry Republic Indonesia No. SK.177/MENLHK/SETJEN/PLS.0/4/2018 (Apriyanto and Kusnandar 2020). One of the missions of Gunung Bromo Education Forest is to preserve the forest area for education, research and development of science and technology. To achieve this, it is necessary to do research on the biomass contained in Gunung Bromo Education Forest as annual inventory data. Therefore, this research aimed to determine the accumulation of biomass in Gunung Bromo Education Forest and to investigate the potential for carbon sequestration across different tree species, age classes and densities.

MATERIALS AND METHODS

Study area and period

This research was conducted at Gunung Bromo Education Forest, Karanganyar District, Central Java Province, Indonesia between July and December 2020. The forest is geographically located at 7º34'21.93"-7º35'38.90" S and 110º59'40.39"-111º0'49.36" E (Figure 1). It has an elevation of 200-337.5 masl with topography undulated to hilly. The climate of Gunung Bromo Education Forest based on the Schmidt and Ferguson is classified as type C (a bit wet). The minimum and maximum air temperatures are 16.8ºC and 39.8ºC, respectively with minimum and maximum relative humidity is 57.9% and 81.4%, respectively and rain intensity of less than 100 mm/day (Darmawan et al. 2021). The land cover at Gunung Bromo Education Forest included mixed forest, mahogany, pine, pine-mahogany, replanted pine, and former nurseries. The land for replanting pine and former nurseries is a moorland that until now has been used by the local community for the production of peanuts, corn and cassava (Abdillah et al. 2021).

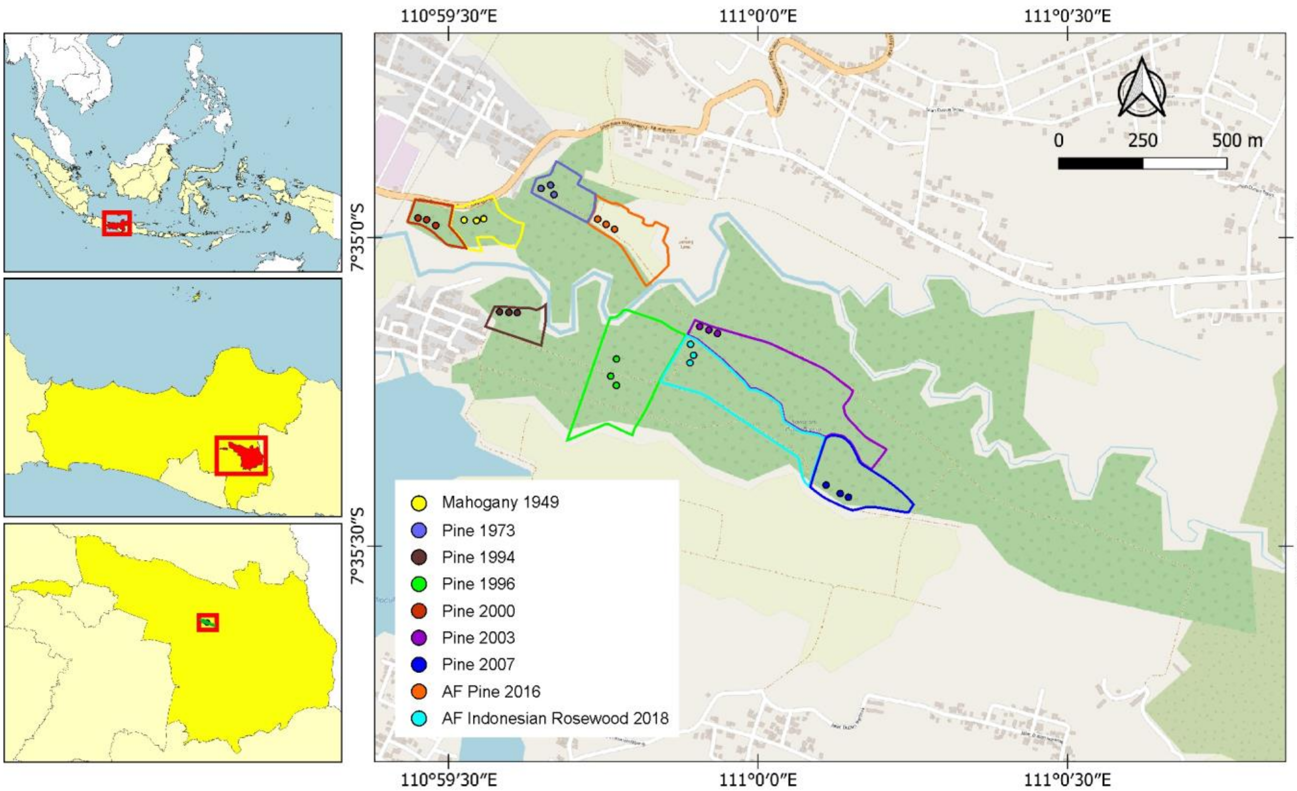

Figure 1. Map of study location of Gunung Bromo Education Forest, Karanganyar, Central Java, Indonesia, with information on tree species and stand age

Table 1. The species-specific allometric equation to calculate tree biomass

Common name	Scientific name	Allometric equation	Source
Pine	*Pinus merkusii*	$AGB= 1.6224D^{1.1012}$	Siregar (2007)[a]
Mahogany	*Swietenia mahagony*	$AGB= 0.903 (D^2H)^{0.684}$	BKPH Wil. XI & MPF II (2009)[a]
Indonesian rosewood	*Dalbergia latifolia*	$AGB=0.746(d^2H)0.6399$	BKPH Wil. XI & MPF II (2009)[a]

Notes: [a] Krisnawati et al. (2012); AGB: aboveground biomass (kg/tree), d= diameter breast-high (cm), H= total tree height (m)

Sampling design and data collection

This study used a purposive sampling method at nine sites representing different tree species and planting years (i.e. Mahogany 1949, Pine 1973, Pine 1994, Pine 1996, Pine 2000, Pine 2003, Pine 2007, Agroforestry Pine 2016, and Agroforestry Indonesian rosewood 2016) each with 3 replicates, resulting in total 27 sampling plots (Figure 1). Plots were made using the method followed Ikhsan et al. (2021). On each land cover, plot measuring 20 m x 100 m and the main sample plot measuring 20 m x 20 m were created (Tohirin et al. 2021).

The tools used in data collection included bamboo stakes, ropes, meters, pens, field books, a digital camera, a range finder, and Global Positioning System. Carbon from biomass analysis was conducted in the Soil Science Laboratory, Faculty of Agriculture, Sebelas Maret University.

Biomass calculation

Tree density

Tree density is the number of individuals of each species in a unit of area and is calculated as follows (Leonika et al. 2021):

$$Tree\ density = \frac{\sum tree\ in\ plot}{plot\ (ha)\ x \sum plot}$$

Tree biomass

The calculation of tree biomass was carried out using allometric equations. This allometric equation is used to determine the relationship between the dimension of the tree and the dry weight of the tree as a whole (Basuki et al. 2022). The allometric formula for each species is presented in Table 1.

Litter and understorey biomass

The litter and understorey biomass was calculated based on the total dry weight (DWt) referring to Oraon et al. (2018) as follows:

$$DWt \frac{DWs}{WWs} xWWt$$

Where: DWt: total dry weight (kg); DWs: dry weight of the example (g); WWs: wet weight of the example (g); WWt: total wet weight (kg)

Carbon sequestration

Carbon sequestration was calculated using the formula from Zhao et al. (2018):

$$C = B \text{ x } \% \text{ C-organic}$$

Where: C: carbon content of biomass, expressed in kilograms (kg); B: total biomass, expressed in kilograms (kg); % C-organic: percentage value of carbon content, amounting to 0.47 or using the value of percent carbon from laboratory analysis

Soil organic carbon

Soil organic carbon calculation used secondary data from previous studies in the form of bulk density values using the sample ring method and SOC using the Walkey and Black method (Eslamdoust and Sohrabi 2018) as follows:

$$SOC\ (t\ ha^{-1}) = \text{bulk density x C-organic (\%) x 100}$$

Statistical analysis

Data were analyzed with One way ANOVA and LSD (*Least Significance Different)* tests to investigate the differences among stand ages and tree species. The relationship between biomass parameters, carbon sequestration and tree age classes was analyzed using regression analysis and correlation test with Fornell-Lacker Criterion. Statistical software used in this study included Microsoft Excel 2016, Systat 13 and Smart PLS.

RESULTS AND DISCUSSION

Aboveground biomass

Biomass is the amount of organic matter contained in a living organism at a certain place and time. The biomass measured in this study included tree biomass, litter and understorey. Based on the results of the analysis showed that tree ages and species had a very significant influence on tree biomass, as well as litter and understorey (Table 2). The Pine 1973 had the highest tree biomass of 461.08 t ha^{-1} and while the AF Pine 2016 and AF Indonesian Rosewood 2018 had the lowest tree biomass with 1.02 t ha^{-1} and 0.39 t ha^{-1}, respectively. The stands biomass is influenced by age, species composition, vegetation density and stand structure, as well as environmental factors (Padmakumar et al. 2018; Slik et al. 2013).

The litter and understorey biomass in the Pine 1973 is the highest with 9.57t ha^{-1} and while the lowest was in the AF Pine 2016 and AF Indonesian Rosewood 2018 with 0.29 t ha^{-1} and 0.16 t ha^{-1}, respectively. In this study, the highest litter biomass was produced by the main crop and secondary crops. Understorey also contributed to the biomass that occurred on the soil surface in each land cover. The biomass of litter and understorey is influenced by the diversity of plants (Liu et al. 2018).

Table 2. Biomass in tree, litter and understorey across various tree cover classes

Tree cover class	Tree density (ind ha^{-1})	Stand biomass (t ha^{-1})	Litter and understorey biomass (t ha^{-1})
Pine 1973	592	461.08^{a}	9.57^{a}
Pine 1994	742	222.31^{bc}	5.40^{bc}
Pine 1996	858	341.55^{ab}	5.42^{bc}
Pine 2000	608	236.70^{bc}	4.13^{bc}
Pine 2003	1358	301.00^{b}	3.50^{c}
Pine 2007	1517	143.11^{cd}	4.07^{bc}
Mahogany 1949	242	358.98^{ab}	5.91^{b}
AF Pine 2016	317	1.02^{d}	0.29^{d}
AF Indonesian Rosewood 2018	258	0.39^{d}	0.16^{d}

Note: Numbers followed by different letters in the same column indicate a significant difference according to LSD (P=0.05)

Table 3. Toral carbon sequestration across various tree cover classes

Tree cover class	Carbon			
	Stands (t ha^{-1})	Litter and understorey (t ha^{-1})	Soil (t ha^{-1})	Total (t ha^{-1})
Pine 1973	216.71^{a}	4.50^{a}	151.47^{c}	372.68^{a}
Pine 1994	104.49^{bc}	2.54^{bc}	162.38^{bc}	269.40^{bc}
Pine 1996	160.53^{ab}	2.55^{bc}	166.55^{bc}	329.63^{ab}
Pine 2000	111.25^{bc}	1.94^{bc}	163.92^{bc}	277.11^{bc}
Pine 2003	141.47^{b}	1.65^{c}	157.76^{bc}	300.88^{bc}
Pine 2007	67.26^{cd}	1.91^{bc}	171.88^{b}	241.05^{cd}
Mahogany 1949	168.72^{ab}	2.78^{b}	158.81^{bc}	330.31^{ab}
AF Pine 2016	0.48d	0.13^{d}	186.50^{a}	187.11^{d}
AF Indonesian Rosewood 2018	0.18d	0.08^{d}	193.32^{a}	193.58^{d}

Notes: Numbers followed by different letters in the same column indicate a significant difference according to LSD (P=0.05)

Total carbon sequestration

The total carbon sequestered in three pools (i.e. tree, litter and understorey carbon and soil organic carbon) is presented in Table 3. The Pine 1973 had the highest tree carbon sequestration with 216.71 t ha^{-1} and the lowest in the AF Pine 2016 and AF Indonesian Rosewood 2018 with 0.48 t ha^{-1} and 0.18 t ha^{-1}, respectively. The carbon stored in the tree is directly proportional to the biomass content, where the higher the amount of biomass, the higher the carbon sequestration (Lutz et al. 2018). Pine, Mahogany, and Indonesian Rosewood stand in productive age had the highest carbon sequestration compared to the juvenile period. In addition, it is also influenced by basal area, stem volume, and so on (Padmakumar et al. 2018). Erkan and Guner (2018) suggest that 50.3% of carbon is stored in Pine leaves and the highest carbon content accumulates in tree trunks at about 80%.

Similarly, the Pine 1973 had the highest litter and understorey carbon of 4.50 t ha^{-1} and the lowest in the AF Pine 2016 and AF Indonesian Rosewood of 0.13 t ha^{-1} and 0.08 t ha^{-1}. The carbon content of litter and understorey is influenced by the shape of the stand, the composition of the understorey species, soil organic matter, soil temperature, soil moisture content, and the quality of the litter on the surface of the soil. Changes in carbon in the soil are influenced by a combination of increased inputs and reduced output within the soil (Na et al. 2021). Carbon derived from litter and understorey can be a primary source of energy for soil microorganisms, especially decomposer microbes (Winsome et al. 2017).

The soil carbon content in the AF Indonesian Rosewood 2018 is not significant with the AF Pine 2016, but both are significantly different from other vegetation cover classes. The AF Indonesian Rosewood 2018 had the highest soil organic carbon with 193.32 t ha^{-1} followed by the AF Pine 2016 with 186.50 t ha^{-1}. The lowest soil carbon was recorded in Pine 1973 with 151.47 t ha^{-1}. In general, the carbon content in the soil is affected by various factors, including soil management. In the AF Pine 2016 and AF Indonesian Rosewood 2018, there were plant cultivation activities, namely tillage and organic fertilization, so that the carbon content in the soil was higher compared to other lands. This is in accordance with Edwin (2016) who states that the carbon content in the soil can be influenced by the intensity of tillage and fertilization activities, where these activities can directly or indirectly affect the amount of carbon in the soil.

The total carbon sequestration in Pine 1973 is significantly different from another land cover (Table 3). The Pine1973 had the highest total carbon sequestration of 372.68 t ha^{-1} and the lowest in the AF Pine 2016 and AF Indonesian Rosewood 2018 of 187.11 t ha^{-1} and 193.58 t ha^{-1}. The amount of carbon sequestration depends on the carbon content above ground and below ground (Na et al. 2021). Zhang et al. (2018) stated that the amount of carbon in land is also influenced by the amount of aboveground biomass which then being accumulated in the soil in the form of SOC. Abera and Wolde-Meskel (2013) stated that factors that affect the carbon content of land include land use, cultivation activities and fertilization.

Potential carbon sequestration with a tree age-class approach

The potential for carbon sequestration in Gunung Bromo Education Forest, Karanganyar District, can be divided into several classes based on the species and age of the tree. The rationale is that each class of tree species and age has different growth rates and biomass accumulation potentials. The species of trees in Gunung Bromo Education Forest, included Pine, Mahogany and Indonesian Rosewood in which these tree species are considered fast-growing trees, thus the interval of the age class is getting smaller. In general, the age interval used has a lifespan of 5 years, but in some conditions, it can be adjusted to the circumstances in the field (Uthbah et al. 2017). Based on the results of the study, the potential carbon sequestration across tree species and age classes is presented in Table 4.

Based on Table 4 and Figure 2, tree age class 1 (K1) has a carbon sequestration potential of 190.34 t ha^{-1}, K2 of 241.05 t ha^{-1}, K3 of 288.99 t ha^{-1}, K4 of 299.51 t ha^{-1}, and K5 of 351.49 t ha^{-1}. In general, the older the tree, the higher the carbon sequestration ability and vice versa. This is because carbon absorption is directly proportional to plant age, where the older the tree has a larger number of leaves than young plants, so carbon absorption in the process of photosynthesis increases. Groover et al. (2017) explained that each tree species has the ability to sequester carbon so that the amount of biomass in the trunk is increasing, besides that it is also influenced by the age of the tree, growth phase, population density and soil and microclimate, which can affect the amount of carbon sequestration. Yin et al. (2012) added that the highest carbon sequestration in trees is on the trunk with average carbon sequestration of about 51.47%.

Relationship between growth parameters and carbon sequestration potential

The relationship between growth parameters and carbon sequestration potential in this study can be seen in Table 5 and Figure 3. This study shows that age has a very strong influence on tree biomass (p=0.851), as well as litter and understorey biomass (p=0.704). Furthermore, litter and understorey biomass has a strong influence on total carbon (p=0.720). In addition, tree biomass has a very strong influence on litter and understorey biomass (p= 0.826) and has a fairly strong influence on total carbon (p= 0.402). The relationship between these parameters can be used as an experimental model as presented in Figure 2.

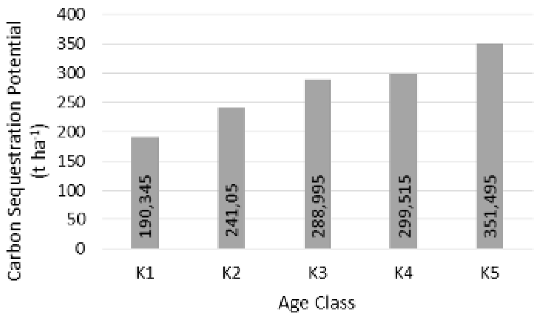

Figure 2. Carbon sequestration potential by tree age class

Table 4. Potential carbon uptake in varying classes based on tree species and age

Tree cover class	Tree age (years)	Age interval	Tree grade	Carbon sequestration potential (t ha^{-1})
AF Indonesian Rosewood 2018	2	1-5	Grade 1	190.34
AF Pine 2016	4			
Pine 2007	13	11-15	Grade 2	241.05
Pine 2003	17	16-20	Grade 3	288.95
Pine 2000	20			
Pine 1996	24	21-30	Grade 4	299.51
Pine 1994	26			
Pine 1973	47	> 31	Grade 5	351.49
Mahogany 1949	71			

Table 5. Relationships between growth parameters and carbon sequestration potential

Parameters	Age class	Litter and understorey biomass	Soil organic carbon	Carbon sequestration potential	Tree biomass
Litter and understorey biomass	0.704**				
Soil organic carbon	0.329	0.224			
Carbon sequestration potential	0.395	0.720**	0.138		
Tree biomass	0.851***	0.826***	0.227	0.402*	
Tree density	-0.021	-0.043	0.279	0.066	-0.102

Notes: * (significant), *** (very significant)

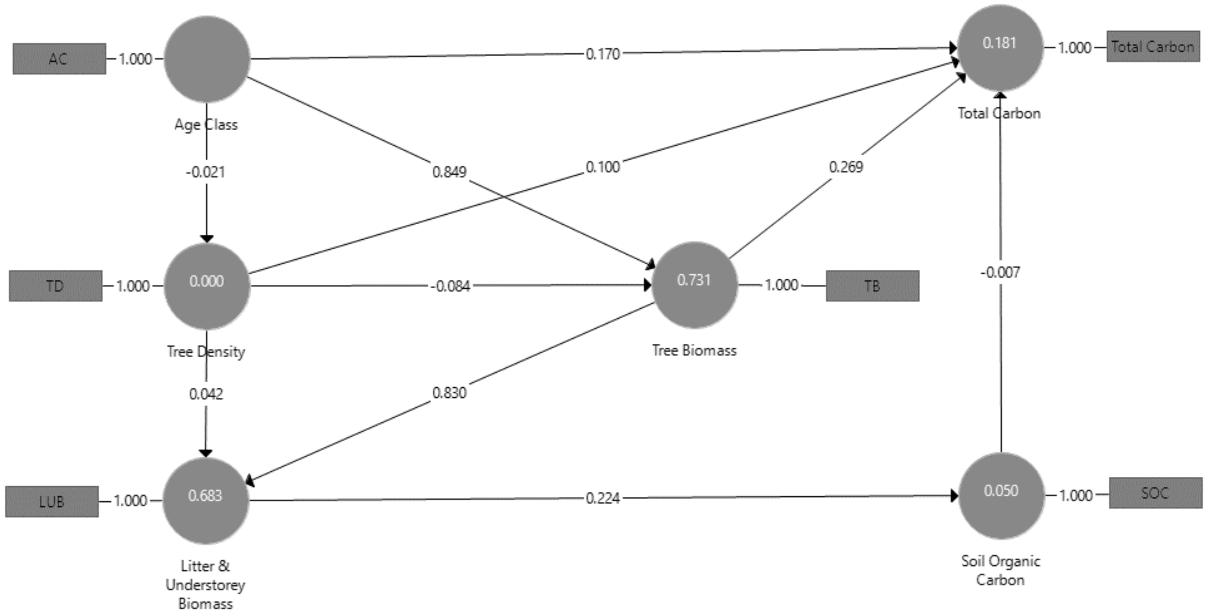

Figure 3. Model depicting the relationship between growth parameters and carbon sequestration potential

In this study, there are two types of effect of growth parameters on the potential for carbon sequestration, namely direct effect and indirect effect. Tree age class, tree density, tree biomass and SOC directly affected the carbon sequestration potential by 17%, 10%, 26.9%, and -0.7%, respectively. Tree age class, tree density, tree biomass and litter and understorey biomass indirectly affect the carbon sequestration potential by 22.6%, -2.3%, -0.1% and -0.2%, respectively. However, the relationship of the parameter to the carbon sequestration potential is indirectly negative, meaning that the parameter is not directly proportional to the carbon sequestration potential. Thus, the effect of the total parameters of tree age class, tree density, tree biomass, litter and understorey biomass, and SOC on the potential for carbon sequestration was by 39.6%, 7.7%, 26.8%, -0.2%, and -0.7%, respectively.

The potential for carbon sequestration can be influenced by various factors. In this study, we focused on the influence of several parameters to show their relationship with the potential for carbon sequestration in varying tree cover types. Gunung Bromo Education Forest has several types of tree cover based on the year of planting to facilitate our analysis to divide into 5 age classes of trees which the older trees had a high carbon sequestration potential (Köhl et al. 2017; Sillett et al. 2020; Uthbah et al. 2017). The age class of trees contributed to carbon biomass by 84.9%. Biomass is continuously increasing by increasing tree size, emphasizing the important role of old trees for carbon sequestration accumulation (Stephenson et al. 2014). Furthermore, the potential for carbon sequestration is also influenced by tree density (Na et al. 2021). In our study, tree density had a contribution to tree biomass of -8.4%, meaning that it is not directly proportional to the age of the tree, as younger trees have a higher population compared to older trees.

Tree density also affected the amount of litter and understorey biomass by 4.2% in which the denser the tree, the higher the amount of litter produced (Ziegler et al. 2013). In addition, tree biomass contributes 83% to litter and understorey biomass, indicating that the older the tree, the more litter is produced (Repo et al. 2021). Litter and understorey biomass affects SOC by 22.4% in which the litter on the soil surface will be distributed by soil fauna into the soil (Darmawan et al. 2021), resulting in an increase of SOC in the soil (Cotrufo et al. 2015; Ma et al. 2018). However, SOC in monoculture plantation forests has a lower SOC compared to agroforestry (Hernández et al. 2016). This is due to the existence of tillage and the addition of organic matter the form of cow manure to increase soil fertility in agroforestry. Based on the findings of this study, the potential for carbon sequestration is influenced by the age of the plant and the density of the tree, which affects the amount of tree biomass and litter and understorey biomass which is then converted as carbon sequestration potential.

In conclusion, the Pine 1973 had the highest biomass accumulation of 470.64 t ha^{-1} and the lowest in the AF Indonesian Rosewood 2018 of 0.55 t ha^{-1}. Similarly, Pine 1973 also had the highest total carbon sequestration capacity with 372.68 t ha^{-1}. Carbon sequestration is influenced by the age of the tree and tree density in which the older the plant and its high density, the potential for carbon sequestration is higher than that of younger plants and low density.

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