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Full Length Research Article

Development of Allometric Model for Estimating Biomass and Carbon Storage of Hybrid Eucalyptus (*E. grandis* × *E. urophylla*) in Industrial Plantation Forests of North Sumatra Province

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ABSTRACT

Hybrid eucalyptus (*E. grandis* × *E. urophylla*) plays an important role in the global carbon cycle because it grows so fast that it is necessary to know how much biomass and carbon are produced. This study aims to develop an allometric equation for estimating the biomass and carbon content stored in Eucalyptus stands. Data were obtained through destructive sampling of 75 trees, then dried in an oven and analyzed to get the most appropriate biomass value and allometric model. The study results showed that the developed polynomial model correlated well with DBH to predict biomass with an R-squared of 97.50. Age 1 with an average diameter of 3.23 cm = 2.50 tons C/ha or 9.17 tons of CO_2e, age 2 with an average diameter of 9.33 = 21.30 tons C/ha or 78.16 tons CO_2e, age 3 with an average diameter of 9.49 cm = 22.50 tons C/ha or 82.57 tons CO_2e, age 4 with an average diameter of 11.62 cm = 38.61 tons C/ha or 141.68 tons CO_2e, age 5 with an average diameter of 12.63 cm = 46.42 tons C/ha or 170.37 tons CO_2e. The carbon stock results show that as the age of the stand increases, the carbon reserves stored also increase.

1. Introduction

Under Indonesian Law Number 41 of 1999, based on its functions, forest areas are categorized into conservation forests, protected forests, and production forests. The function of these forests is influenced by the condition of the local ecosystem, the silvicultural system, and the management perspective to be achieved. When considering carbon in the context of land management activities, it is important to consider the overall management objectives associated with a plot of land, the carbon stocks on different lands, the carbon stocks on different land resources, and the carbon flows between them. Carbon accumulates in plants and soil. Carbon is stored in living trees, dead trees, fallen wood, undergrowth, and soil in forests. It can be transferred to various sources and into the atmosphere. The industrial side of the forest carbon cycle is also considered, as carbon can be obtained from wood products and replace fossil fuel-based products. In ecosystems, carbon management often focuses on determining the amount of carbon stored in biomass and soil and the rate at which new carbon is absorbed into biomass (Janowiak 2017).

Indonesia has allocated a forest area of 120 million ha or 64% of its land area. The production forest area in Indonesia comprises 68.8 million ha, conservation forests comprise 22.1 million ha, and protected forests comprise 29.6 million ha (KLHK 2020). Plantation forests, which are part of production forests, have an area of 4.3 million ha (KLHK 2020). Plantation forests are developed to increase the added value of forests, foreign exchange, land productivity, environmental quality, and employment opportunities.

The development of the human population and its activities causes significant forest clearing, resulting in climate change due to increased greenhouse gas (GHG) emissions in the atmosphere. Forests are important in the net zero emissions (NZE) process because they are both a source and sink of carbon. NZE refers to the condition where the amount of greenhouse gas emissions released into the atmosphere equals the amount absorbed from the atmosphere. Sustainable and progressive community development can be realized by reducing CO_2 emissions and creating neutral, green and sustainable climate conditions (Raihan and Tuspekova 2023).

The amount of forest biomass is determined by the density, soil fertility, diameter, height and specific gravity of wood (Heriyanto et al. 2020). Producing precise and accurate biomass forecasts is a challenge for several reasons. First, an impartial forest inventory project with reliable measurements of tree traits is needed. In addition, a biomass estimation model is required to accurately represent forest inventory data (Dutcâ et al. 2020). Forest biomass research is carried out with various objectives, such as knowing its energy potential (Präger et al. 2019), making a significant contribution (Zhao et al. 2018), and potential carbon reserves (Chieppa et al. 2020).

Some studies suggest that forest cover loss contributes to 6–7% of global carbon emissions (Baccini et al. 2012; Wood et al. 2019). In addition to the issue of climate change, loss and deforestation are also related to poverty and food security. Tropical forests are mostly found in developing countries where most people are low-income, heavily forest-dependent, and marginalized. All these issues must be considered in developing climate change mitigation and adaptation programs (Djalante et al. 2021; Oldekop et al. 2019; Roe and Elliott 2010; White and Martin 2002). Conserving and maintaining carbon stocks in tropical forests is becoming increasingly important in addressing climate change, conserving biodiversity, and poverty alleviation (Darmawan et al. 2022; Qirom et al. 2021; Van de Perre et al. 2018).

Eucalyptus is a type of plant that grows quickly and is one type that is developed in industrial forest plantations to supply raw materials for the pulp industry. Hybrid eucalyptus (*E. urophylla* × *E. grandis*) was developed to produce plants that are more resistant to pests and diseases and can grow in the highlands of eucalyptus species that grow well (Mindawati et al. 2010). Hybrid eucalyptus growth is fast and can bind carbon in the atmosphere, thus playing an important role in the global carbon cycle (Viera and Rodríguez-Soalleiro 2019). Plant diversity in general, and woody plant diversity in particular, has an important role and value for the existence and development of humanity because it is considered a resource and carbon sink. It also helps reduce greenhouse gas concentrations by absorbing large amounts of carbon from the atmosphere (Hop et al. 2023). Several types of industrial plantations have such characteristics, one of which is eucalyptus. In connection with the problem of carbon sequestration in overcoming global warming, this research aims to determine the amount of biomass and carbon content stored in eucalyptus plantation forest stands to obtain potential and sustainable management.

2. Materials and Methods

2.1. Collection of Data

2.1.1. Research location and time

The study was conducted on stands of hybrid eucalyptus (*E. grandis* × *E. urophylla*) in the Aek Nauli sector, PT Toba Pulp Lestari Tbk. Aek Nauli sector has a concession of 20,360 ha with a productive crop area of 9,027 ha and a 5-year logging cycle. The research location is at 98° 50' 00" – 99° 10' 00" East Longitude and 02° 40' 00" – 02° 50' 00" North Latitude with an altitude of 900–1200 m above sea level, climate type A (very wet). The average rainfall in 2019 –2023 was 237 mm/month, with the highest in November and the lowest in February. Laboratory activities for eucalyptus biomass were carried out at the Wood Laboratory of PT Toba Pulp Lestari Tbk – Parmaksian. Research data collection activities were carried out in September–October 2023. The research location map is presented in **Fig. 1**.

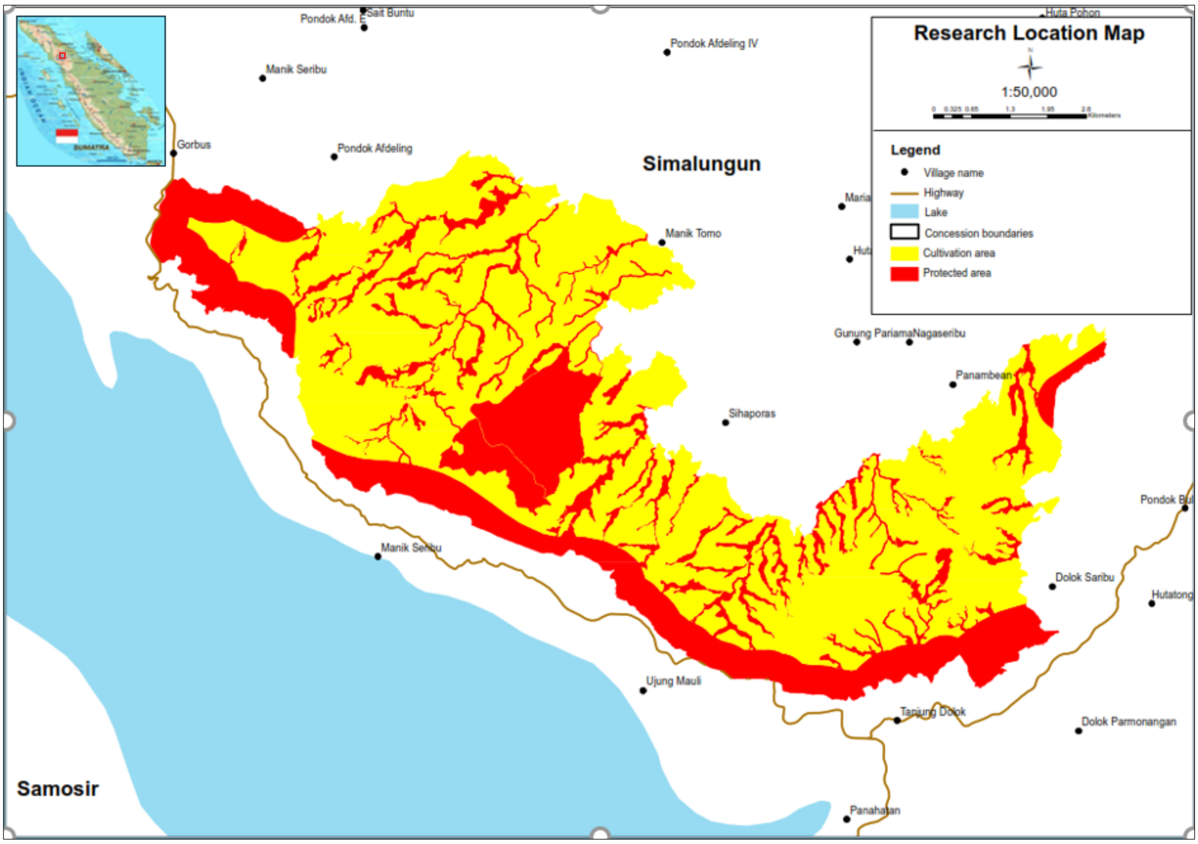

Fig. 1. Research location map.

2.1.2. Tools and research materials

This research used several data collection tools, such as GPS, Chainsaw, and others, as presented in **Table 1**.

2.1.3. Determination of the research plot

A compartment is a small unit for plantation forest management. There are 45 stand inventory plots (number and diameter), each representing a different age class (1–5 years) with three compartments and three sample plots in each compartment (**Fig. 2**).

Table 1. Tools and research materials

Category		Description
Tools	GPS	Record coordinates and tie points
	PC/Laptop	Running software
	Meter device	Measure the distance and circumference of trees
	Chainsaw	Uprooting and chopping trees
	Scales	Measuring the wet weight of the sample
	Oven	Drying the sample moisture content
	Ms Word	Prepare reports
	MS Excel	Calculating the equations
	SPSS	Processing statistical data
Material	Eucalyptus	Source of biomass data

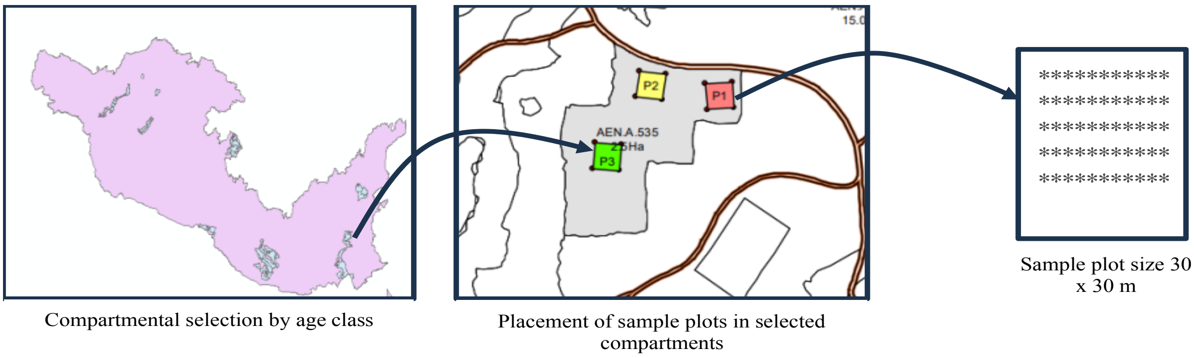

Fig. 2. Research plot.

2.1.4. Type of data

The data types collected consisted of primary data, namely data obtained directly from the field and secondary data, which is information related to research. The types of research data are shown in **Table 2**.

Table 2. Type of research data

Type of data	Method	Sources
Vegetation data: diameter, number of stands, wet weight (stems, leaves, twigs, and bark) and diameter per section	Vegetation analysis	Field data

2.1.5. Data collection technique

The data collection was conducted through several stages, from the "determination of research plot" to the "allometric model" stage. More details about the stages of the data collection technique are shown in **Fig. 3**.

2.1.6. Stand inventory and biomass calculation

Determination of sample plots using the purposive sampling method by considering plant age with a plot size of 30 × 30 m adjusted to Landsat 8 spatial resolution (Knight and Kvaran 2014). The inventory activity took data on the diameter of chest height and the number of stands in one plot. The diameter distribution was then obtained so that the class and interval of the tree diameter can be determined. Sample trees were taken as many as 15 trunks in each age class based on the tree diameter class and the number of sample trees, as many as 75 trunks. Model preparation uses 50 data samples and 25 samples as validation (Wirabuana et al. 2021).

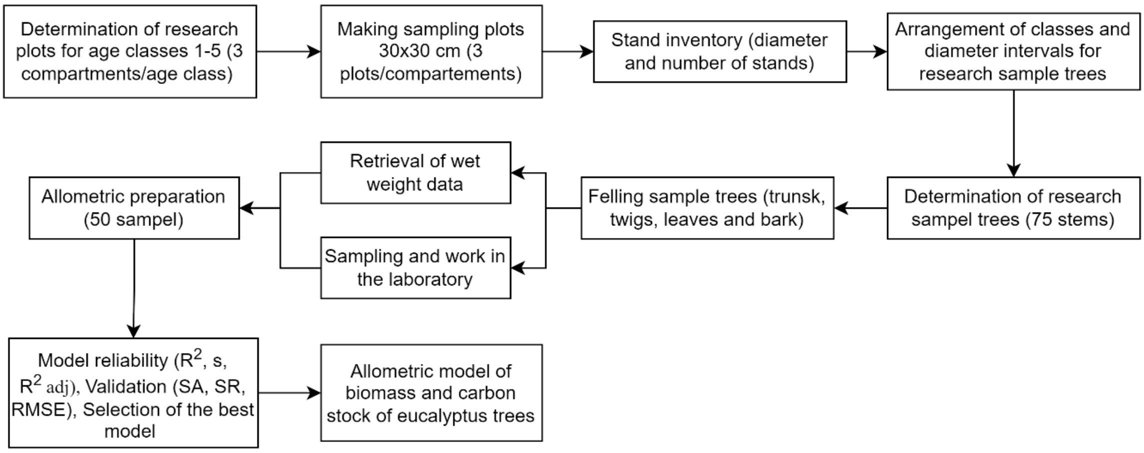

Fig. 3. Data collection technique.

To determine the biomass of sample trees, the following activities were carried out: (1) the wet weight of the stems, leaves, twigs and bark of the sample trees was weighed directly in the field, (2) the sample trees had a minimum diameter of 3 cm and a maximum stump height of 5 cm when felled. The length of the tree trunk is measured from the base to a minimum diameter of 3 cm, then divided into five parts, namely 0% (base), 25%, 50%, 75% and 100% (tip), with a thickness of 3 cm (Martins et al. 2020). Division of tree trunk length as in **Fig. 4**, and (3) leaves, twig and tree bark samples were taken, each part weighing 0.5 kg for biomass analysis.

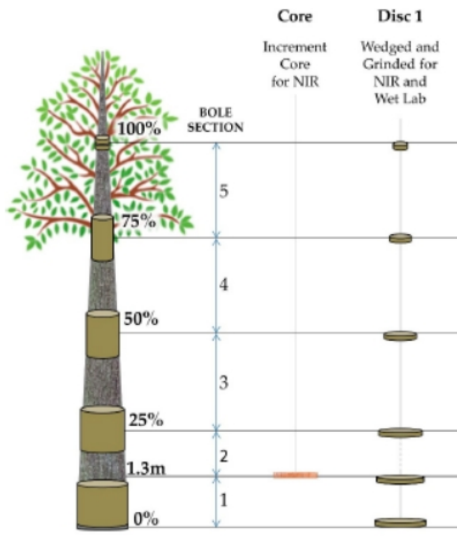

Fig. 4. Distribution of sample tree trunks (modified from Martins et al. 2020).

The dry weight of the leaf kiln and bark was obtained by drying in an oven at 80 °C for 24 hours, while the twigs and stems are dried in an oven at 105 °C for 24 hours. Tree-specific gravity was obtained by averaging wood samples at five positions along the tree. The specific gravity of all trees was based on frustum volume by averaging tree-specific gravity measured by area (Martins et al. 2020; Singh et al. 2022).

2.2. Data Analysis

2.2.1. Biomass analysis

Data on the wet weight of stems, leaves, twigs, and bark of sample trees was obtained by weighing directly in the field using a scale. The moisture content is calculated using Equation 1 (Haygreen and Bowyer 1982).

$$MC = (WW\text{-}DW)/DW \times 100\% \quad (1)$$

where *MC* is the moisture content (%), *WW* is the wet weight of the sample (g), and *DW* is the dry weight of the sample (g).

The next stage was creating a regression model to estimate plant biomass. The independent variable used is the diameter independent variable. DBH has a low measurement error rate of less than 3 % (Brown et al. 1995; Wongchai et al. 2020) and has coefficient determination of 0.935 (Purwanto et al. 2022). The dependent variable used is total biomass storage in plants, which is the sum of the biomass storage in stems, twigs, leaves, and bark. The model tested only uses diameter data as in Equations 3, 4, and 5.

$$\textit{Exponential: } Y = a \exp(b\, D) \quad (3)$$

where Y is Biomass, a is the initial constant, b is the growth constant, and D is the diameter at breast height (DBH).

$$\textit{Polynomials: } Y = aD^2 - bD + c \quad (4)$$

where Y is Biomass, a is a quadratic coefficient, b is a linear coefficient, c is constant, and D is the diameter at breast height (DBH).

$$\textit{Logarithm: } Y = a \ln(D) - b \quad (5)$$

where Y is Biomass, a is scale constant, b is shift constant, and D is diameter at breast height (DBH)

The coefficient of determination is a comparison between the sum of regression squares (*SSR*) and the total sum of squares (*TSS*) to see the strength of the relationship between variables weight and diameter, with Equation 6.

$$R^2 = RSSR/TSS \times 100\% \quad (6)$$

Standard deviation was measured to show the magnitude of the deviation of the estimated value from the actual value, with Equation 7.

$$s = \sqrt{(\textstyle\sum(Ya-Yi)^2)/((n-p))} \quad (7)$$

where Ya is the actual value, Yi is the estimated value, $(n-p)$ is the residual degrees of freedom, and s is the standard deviation. The best model is the model with the smallest variance value.

The coefficient of determination was corrected to see the level of accuracy of the coefficient if there are many different D variables, with Equation 8.

$$s = \sqrt{(\textstyle\sum(Ya-Yi)^2)/((n-p))} \quad (8)$$

where R^2 *adj* is the corrected coefficient of determination, p is the number of variables in the regression, n is the number of objects analyzed, and R is the coefficient of determination. The best model has an R^2 adj value close to 100%.

A good allometric model has an Aggregate Deviation (AD) value of -1 to +1, obtained from the difference between the sum of its actual values and the theoretical value as proportional to the presumptive value. The Mean Deviation (MD) value is the absolute sum of the differences between the number of conjectures and the actual value that caldulated using Equations 9 and 10.

$$AD = \frac{\left(\sum_{i=1}^{n} \hat{y} - \sum_{i=1}^{n} y\right)}{\sum_{i=1}^{n} \hat{y}} \quad (9)$$

$$MD = \frac{\left|\sum_{i=1}^{n} \frac{\hat{y} - y}{\hat{y}}\right|}{n} \quad (10)$$

Root Mean Square Error (RMSE) is based on the total square of the deviation between the model results and the observations, calculated using Equation 11.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y} - y)^2}{n}} \quad (11)$$

2.2.2. Model selection

The best model is selected by giving a score to the model so that a total score is obtained on each model (Mulyana et al. 2020). The ranking is compiled based on the total score, and the best model is the model with the highest total score. *AD*, *MD*, *s*, and *RMSE* are the criteria used that calculated using Equation 12.

$$Score = \sum_{i=1}^{n} \left(\left(\frac{|TV| - |max|}{|min| - |max|} \right) x\ (n-1) \right) + 1 \quad (12)$$

TV is the test value for each criterion (*RMSE*, *s*, *AD*, *MD*), *min* is the smallest value of each criterion, *max* is the largest value, and *n* is the number of models tested.

2.2.3. Biomass and carbon storage

Biomass storage per ha can be estimated using Equation 13 (BSN 2011).

$$Bn = \sum \frac{Bx}{1000} \times \frac{10000}{Lp} \quad (13)$$

where *Bn* is the biomass content per ha for each tree in each plot (tons/ha), *Bx* is the biomass content of each tree in each plot (kg), and *Lp* is the area of the measuring plot (m^2). Carbon storage is calculated using Equation 14 (Brown 1997).

$$C = B \times 0.5 \quad (14)$$

where *C* is the carbon savings (tons/ha), *B* is Biomass (tons/ha), and *0.5* is the carbon content.

3. Results and Discussion

3.1. Biomass Proportion

Biomass of hybrid eucalyptus (*E. grandis* × *E. urophylla*) increases markedly with the age of the stand (**Fig. 5**). Based on the analysis showed that the biomass content of hybrid eucalyptus increases with the age of the stand, while the age of the stand does not affect the biomass of leaves, twigs, and bark of trees.

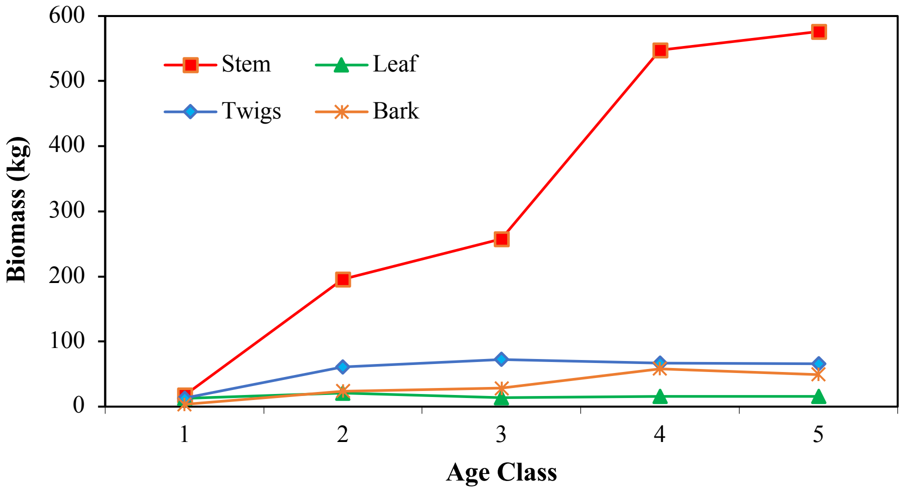

Fig. 5. Biomass of every tree-parts of hybrid eucalyptus.

The data in **Table 3** shows that the stem has the largest biomass. In the 1-year age class, the largest proportion of biomass is stem at 37%, twigs at 28.19%, leaves at 27.33% and bark at 7.48%. At the age of 2–5 years, the average proportion of the largest biomass is stemmed by 76.21%, twigs by 12.86%, bark by 7.69% and leaves by 3.23%. The largest increase in biomass occurred in the second year at 546.6% compared to the first year. The smallest increase in biomass was found in the fifth year of 2.61%. At the age of 3 years, the increase in biomass was only 23.72%, and at the age of 4 years, it increased by 85.14%.

Table 3. Biomass of every tree-parts of hybrid eucalyptus

Age class	Biomass (kg)				
	Stem	Leaf	Twigs	Bark	Total
1	17	13	13	3	47
2	195	21	61	24	301
3	258	14	72	28	372
4	547	16	67	58	689
5	576	16	66	49	707

The large percentage of stem biomass, along with the plant's age and diameter, shows that biomass allocation is prioritized to the stem to optimize the translocation process (Wirabuana et al. 2020). In line with research conducted by Simamarta and Tambunan (2015) on the model of estimation of biomass on the soil type of *Eucalyptus urophylla* in planting forests with the finding of an increase in the biomass of stems, branches, and twigs as the age of plants increases.

3.2. Equations Model Equations

The three models obtained the R-square values of 62.20%, 93.40%, and 97.50%, respectively, for the logarithm, exponential, and polynomial models (**Table 5**). In line with one of the carbon stock measurement studies conducted by Nuraini et al. (2022) using three types of models, namely linear, exponential, and polynomial, it was found that the best model chosen for carbon estimation was the polynomial model because the value of the coefficient of determination (R^2) was higher than other models. The highest R^2 value is used in preparing the carbon estimation model because the higher the R^2 value can indicate the ability of the dependent variable value to the independent variable to predict the carbon value. The polynomial model has a y function of $0.499D^2 - 2.863D + 6.136$ with an R^2 value of 97.50.

Table 4. Estimation model

Type	Equation	R^2	R^2 adj	RMSE	s	AD	MD
Logarithm	$Y= 40.169*\ln(D) - 53.992$	62.20	61.40	12.21	12.46	0.19	0.29
Exponential	$Y = 1.199 * e^{(0.291*D)}$	93.40	93.30	7.01	7.16	0.04	0.19
Polynomials	$Y= 0.499D^2 - 2.863D+6.136$	97.50	97.40	3.69	3.77	0.07	0.13

Table 5. Estimation model rank

Model	Score				Total Score	Ranking
	RMSE	s	AD	MD		
Logarithm	1.00	1.00	1.00	1.00	4.00	3
Exponential	2.22	2.22	3.00	2.27	9.71	2
Polynomials	3.00	3.00	2.56	3.00	11.56	1

3.3. Polynomial Model Equations

In the polynomial estimation model equation test between biomass and diameter, the results of measurements in the field provided a strong correlation between diameter at breast height and biomass in hybrid eucalyptus. The results of regression data processing show that the coefficient of determination (R^2) is 0.9751, which means 97.51%. This correlation relationship has a positive polynomial pattern with the model equation $Y= 0.499 D^2 - 2.863D + 6.136$, where x is the tree's diameter at breast height/DBH, and y is the biomass. The magnitude of the correlation between the two is 0.9751, which indicates a strong relationship. This is in line with research conducted by Ribeiro et al. (2023) on developing allometric equations for estimating biomass of eucalyptus and native Cerrado vegetation, which determines aboveground carbon based on diameter at breast height and tree height. Stem biomass ranged from 74.32% to 78.98%, branch biomass ranged from 11.34% to 14.04%, and leaf biomass ranged from 9.68% to 11.64%. Likewise, the bark, sapwood and heartwood percentages were estimated at 13.5, 45.76 and 39.75, respectively. R^2 values for stems (0.94), branches (0.95) and leaves (0.97) (**Fig. 6**).

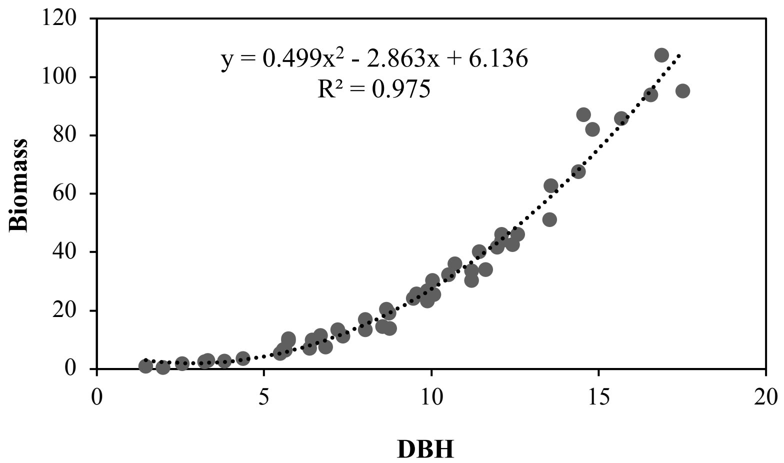

Fig. 6. Biomass Polynomial Model Results with Diameter (DBH).

The allometric expression of each aboveground tree morphological compartment of biomass and carbon follows a logarithmic function with a high correlation for each part of the tree. In this case, the biomass and carbon stock of the hybrid eucalyptus significantly correlated with one predictor, namely the tree's diameter, as shown in **Table 6**. This aligns with one of the studies that found the results of aboveground biomass and carbon deposits *E. grandis* correlate with tree diameter (D) (Onrizal et al. 2018).

Quantifying forest biomass carbon (C) stock change is important for understanding forest dynamics and their feedback with climate change (Xu et al. 2016), as it is a relevant component of carbon stocks and assessment of climate change mitigation potential (Huy et al. 2016). Therefore, reliable biomass estimation is essential for monitoring forest conditions and supporting decision-making in forest management (Ubuy et al. 2018). Biomass estimation can be done using a variety of methods, including direct application of allometric equations, multiplying stand volume by wood density, or using a biomass expansion factor, which is a measure of the ratio of volume to biomass (Forrester et al. 2017; Yang et al. 2023). The preparation of allometric models of tree biomass began to develop rapidly after 2000. From 2000 to 2012, about 77% of the published literature presented allometric model information to estimate biomass value (Krisnawati et al. 2012). This development aligns with climate change issues and the follow-up of Indonesia's commitment to reduce greenhouse gases (GHG). The allometric equation Model to estimate the value of carbon mass has not been done. More information is available, including allometric models to estimate biomass values of trees and tree volume, as in the monograph allometric model issued by the Ministry of Environment and Forestry and compiled by Krisnawati et al. (2012).

Table 6. Carbon stock estimation

Age Class	Average Diamater	Biomass		Carbon stock	
	(cm)	(kg)*	(ton/ha)	(ton C/ha)	(ton CO_2e)
1	3.23	4,049.36	5.00	2.50	9.17
2	9.33	34,502.50	42.60	21.30	78.16
3	9.49	36,445.59	44.99	22.50	82.57
4	11.62	62,541.47	77.21	38.61	141.68
5	12.63	75,202.78	92.84	46.42	170.37

Notes: * is total biomass from one age class (9 plots) with a total plot area = 8100 m^2.

According to Rauf (2011), biomass and total carbon stands (vegetation) in an area or land unit describe how much the ability of the area to absorb (anchor) CO_2 from the air and at the same time, convey the stored energy (potential) that is or is owned by the area or land unit. The denser the vegetation of an area, the higher the ability to anchor air CO_2 and energy stored in that area, and vice versa. The results showed that the hybrid eucalyptus in industrial plantation forests contributes enough to the absorption of greenhouse gases, especially CO_2 gas from the air. Apart from that, Heriyanto et al. 2023 state that young trees' growth has greater potential to absorb and reduce carbon dioxide levels from the air than older trees.

4. Conclusions

This study concludes that the best allometric model for hybrid eucalyptus biomass is polynomials $Y= 0.499D^2 - 2.863D+6.136$ with a total score of 11.56 and can be explained well by using a model consisting of the variable D. The amount of biomass increases with the age and diameter of the stand. The results of the carbon stock also showed that the more age the stand had, the greater the amount of carbon stored. Harvesting at five years is expected to produce sustainable forest management. Future research is recommended to be able to search for allometric biomass models for each age class.

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