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The allometric equations for estimating above-ground biomass in a 50 years-old secondary forest in East Kalimantan, Indonesia

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Abstract. *Karyati, Karmini, Widiati KY. 2023. The allometric equations for estimating above-ground biomass in a 50 years-old secondary forest in East Kalimantan, Indonesia. Biodiversitas 24: 1482-1492.* Secondary forests, formed through several disturbances over the decades, have important roles in ecological and economic aspects. One of their roles in ecological aspects is the potential to store carbon. Therefore, this study aimed to develop allometric equations for estimating above-ground biomass and carbon stock in a 50 years-old secondary forest. In this field, 30 trees representing the dominant species and diameter class distribution were selected and cut down. The dry biomass of the tree's parts, including leaves, branches, and trunks, was assessed using the destructive method. The relation between trunk dry biomass and Diameter at Breast Height (DBH) showed moderate adjusted R^2 value (0.641). Moreover, moderately strong relationships were shown by above-ground biomass with DBH (adjusted R^2 of 0.516). The allometric equation to estimate above-ground biomass in 50 years-old secondary forest is useful for estimating the carbon potential in other areas of the same age, especially with a similar land use history. Information regarding biomass and carbon stock is important for forest management in general. It can assess carbon stocks, sequestration rates, and potential emissions from forests subjected to a succession process.

Keywords: Abandoned land, allometric equation, biomass, carbon stock, secondary forest

INTRODUCTION

Secondary forest components with high species density are significant carbon reservoirs and can play a crucial role in mitigating climate change (Ekoungoulou et al. 2014). It provides environmental benefits from ecological, social, economic, and other perspectives. Secondary forests that are sustainably managed offer significant benefits towards enhancing the resilience of ecosystems and communities, optimizing the role of vegetation in forests for carbon absorption and storage, and providing many other crucial environmental services (FAO 2016). In the tropics, it can sequester carbon up to 20 times faster than older primary forests, which does not consider spatially induced regrowth patterns and factors of increased disturbance (Heinrich et al. 2021). Carbon accumulation has shown a rapid increase with age, particularly when tree planting and tending activities are employed, as they can significantly accelerate this process. Increasing the possibility of using carbon values as an attractive economic incentive can improve forest conservation efforts (Pothong et al. 2021).

A secondary forest is a system that can produce, store, or release carbon. Therefore, the secondary forest can produce a larger carbon stock with more trees. The dry mass of a tree or shrub's above-ground standing live or dead matter is typically expressed as a mass per unit area. The biomass calculation in secondary forests is commonly performed by estimating the volume of wood obtained from logging activities during tree harvesting. Furthermore, biomass estimation is crucial in supporting efforts to reduce carbon dioxide emissions by enhancing forest carbon stocks (Zaenal et al. 2020). However, most studies on biomass are still limited to certain areas, forest types, and species. Therefore, further study should be conducted on other forest types, specific growth forms, and large tree diameter classes (Anitha et al. 2015). In addition, new allometric equations are formulated to predict the above-ground biomass of secondary forests. In contrast, the new allometric equations have different types compared to several others from the results of previous studies.

Secondary forest is often abandoned after shifting cultivation and traditional gardens. However, it plays a vital role in ecological and economic aspects (Karyati et al. 2013; 2018; Karmini et al. 2020a,b; 2021). Several allometric equations that can be used to estimate above-ground biomass and carbon stocks have been reported (Manuri et al. 2016; Mardiatmoko 2016; Maulana 2014; et al. 2016; Prayogo et al. 2018; Karyati et al. 2019a,b; 2021; Poleuleng et al. 2020; Sadono et al. 2021; Basuki et al. 2022; Suprayogi et al. 2022). However, equations for estimating this biomass and carbon stocks have been subjected to several disturbances, such as forest fires, shifting cultivation, and traditional gardens. Karmini et al. (2021) showed a 50-year-old secondary forest in the Province of East Kalimantan, Indonesia, with unique characteristics differentiating it from other areas. For example, a 50-year-old secondary forest has many trees with Moraceae and Euphorbiaceae's most dominant families, with the *Macaranga motleyana, Artocarpus elasticus*, and *Symplocos fasciculata* species. Besides biodiversity, the 50 years old secondary forests in East Kalimantan also have economic value with a stumpage estimation of USD28.73 ha^{-1}. Therefore, the prior study suggests preserving the forest for sustainability.

As described above, the presence and opportunities for utilization encourage the need for study on biomass and carbon stock. Therefore, this study aims to develop allometric equations to estimate above-ground biomass in 50 years-old secondary forests subjected to several disturbances. It can be used as consideration and decision-making in general secondary forest management in the tropics and East Kalimantan.

MATERIALS AND METHODS

Study site

This study was conducted in a 50 years-old secondary forest in the Air Putih area, Samarinda Ulu District, Samarinda City, East Kalimantan Province, Indonesia. The forest is located on the side of the road connecting Samarinda and Tenggarong Cities in Kutai Kartanegara Regency. The study site is located at coordinates 117º6'29.7641 "East longitude 0º26'56.5901 "South latitude, as shown in Figure 1. The site and plot of the study on ecological and economic aspects are similar, as reported by Karmini et al. (2021). The land use history in the location was obtained from landowner interviews. Furthermore, forest clearing activities for swidden cultivation were conducted in 1969. Shifting cultivation activities were stopped because the forest fires in 1983 had burned all the vegetation in the area. The next land use is the cultivation of local rubber and fruits. The land remained unused for several years to facilitate study. It should be noted that the area possesses considerable coal potential.

Data collection

Measurement of biomass in the field

In 50 years-old secondary forest, 30 samples of trees with a Diameter at Breast Height (DBH) of >10 cm were selected to represent the composition of tree species and DBH class. Meanwhile, the selected sample trees included 17 species of 13 genera of 11 families. The density with a DBH size of > 5 cm was 437 trees consisting of 38 species, 30 genera, and 19 families in a study plot measuring 0.4 ha (Karmini et al. 2021), as illustrated in Figure 2A. The DBH was measured using a diameter tape, and the maximum size was the biggest among the tree samples. The minimum DBH size is the smallest among the DBH sizes of tree samples. Considering the standard deviation values, the DBH and H sizes range between the minimum and maximum. Tree samples were cut down by using chainsaws under harvesting regulations, as shown in Figure 2B.

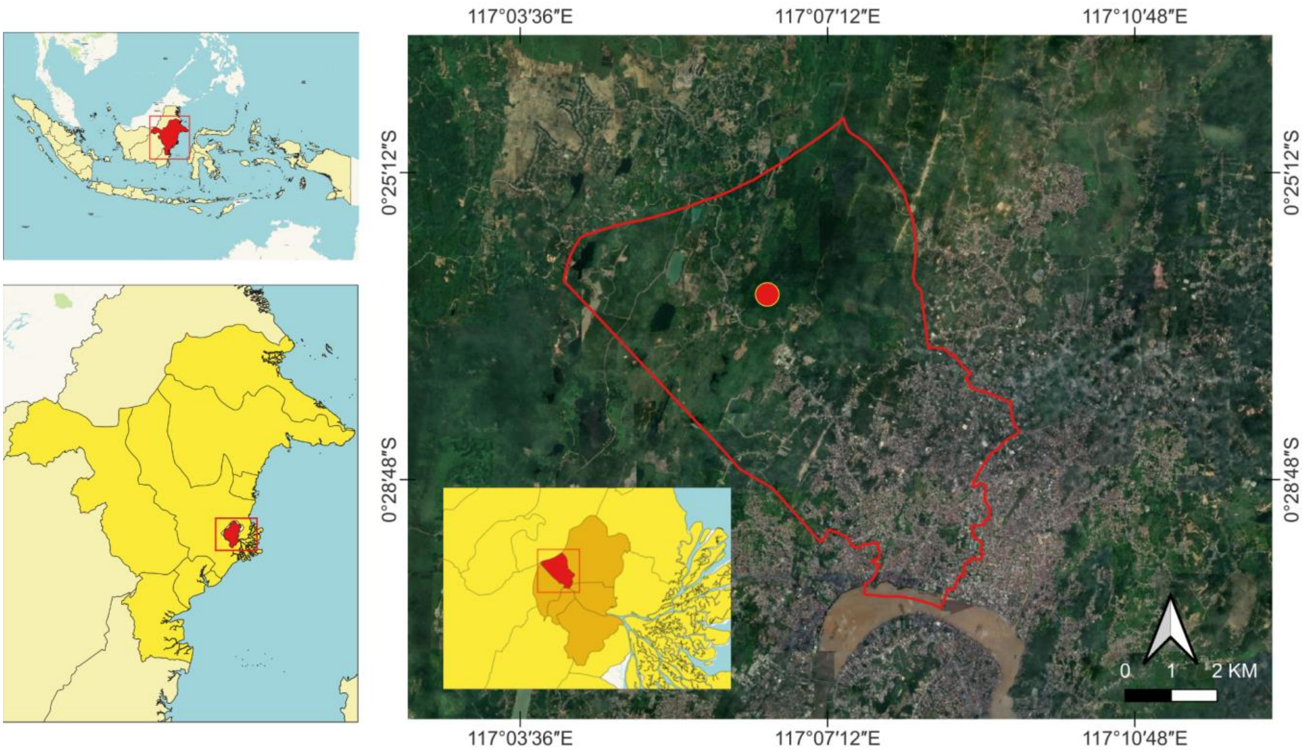

Figure 1. Map of study site in Air Putih area, Samarinda, East Kalimantan Province, Indonesia

Figure 2. A. A 50 years-old secondary forest, B. Hewing of a tree sample, C. The cutting of tree trunks sample into 1-meter length fractions, D. Weighing the fresh weight of trunk fraction 1 meter in the field

Subsequently, the total and bole heights were measured immediately after the tree was hewed. The fallen tree trunk was divided into several fractions, measuring 1 m long, as shown in Figure 2C. The next step was to separate the parts of the tree consisting of leaves, branches, and trunks. The distribution of sample fractions followed the regulations of the Ministry of Forestry Indonesia (BSN 2011).

After the separation, the fresh weight of the tree fractions was weighed using an appropriate scale (Figure 2D). Furthermore, three samples of thick trunk discs measuring 2-5 cm were collected when the felled trees had fewer than ten segments to determine the dry weight of tree trunks, and four samples were taken for segments above 10. In addition, five branch samples measuring 20-30 cm in length were collected for each tree sample, along with five leaf samples weighing between 100-300 g. Moreover, samples of trunk discs and their fresh weight were also measured to calculate the Wood Specific Gravity (WSG). All disc and branch samples were collected in several plastic boxes, each measuring 50 cm long, 35 cm wide, and 30 cm high in the field. These plastic boxes are then taken to the laboratory.

Analysis of dry weight in the laboratory

All leaf samples were dried in the laboratory oven at 80°C for 48 hours until a constant weight was obtained. Meanwhile, the branches and trunk fraction samples were oven-dried at 105°C for 96 hours, as shown in Figure 3A. The subsequent procedure involved the measurement of all leaf, branch, and trunk fractions samples utilizing a digital analytical balance with a precision level of 0.01 gram, as shown in Figures 3B and 3C.

The wood density of each disc sample was measured using the water displacement method (Chave 2006). First, the saturated volume was obtained using a water-filled container and then weighed using a digital scale with a minimum accuracy of 0.01 grams. The disk samples were then dried in a well-ventilated oven at 105°C for 48-72 hours until a constant weight was obtained. Subsequently, the disk samples were weighed to obtain the dry weight.

Data analysis

The Wood Specific Gravity (WSG, g cm^{-3}) of each disc sample was calculated by dividing the total dry weight (*dw*, kg) by the saturated volume (V, cm^3) (Chave 2006). The oven-dry weight total of each tree part was measured using the following formula (BSN 2011):

$$dw = (sdw \times fw) / sfw$$

Where: *dw*: total dry weight (kg); *sdw*: dry weight of the sample (g); *fw*: total fresh weight (kg); *sfw*: fresh weight of the sample (g)

The quadratic polynomial equations were used to show the relation of DBH and Ht, as well as DBH and Hb, as follows:

$$y = a + bx + cx^2$$

This study formulated the AGB exponential equations as follows:

$$y = ax^b$$

Where: y = total dry weight or biomass of each plant part, such as trunk, branch, leaf, and Total Above-Ground Biomass (TAGB) (kg); x = Diameter at Breast Height (DBH, cm), total tree height (Ht, meter), tree bole height (Hb, meter), and the product of square DBH and total height ($DBH^2 \times Ht$) (cm^2 m), and the product of square DBH and bole height ($DBH^2 \times Hb$) (cm^2 m), '*a*' and '*b*' = coefficients.

This study calculated the multiple coefficients of determination. Testing the overall significance of an equation in terms of R^2, according to Gujarati and Porter (2009), could be conducted through computation $F = (R^2/(k - 1))/((1 - R^2)/(n - k))$ where R^2 was the coefficient of determination, (k - 1) was numerator df and (n - k) was denominator df. The best equation among tested equations was selected based on values of adjusted R^2, Mean Square Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and Akaike's Information Criterion (AIC) equations.

Comparison among various allometric equations was performed by using the quantitative descriptive analysis. In addition, the AGB and carbon stock were estimated, resulting from prior studies in other locations and the equation from this study. The amount of carbon stock is determined by multiplying the Total Above-Ground Biomass (TAGB) by 0.50 (IPPC 2019). The carbon stock should be calculated to determine the amount in a 50-year-old secondary forest. Sutaryo (2009) stated that approximately 50% of carbon is sequestered in forest vegetation. Therefore, the remaining 50% of forest carbon is saved in other variables besides vegetation.

Selected tree samples

The number of tree samples based on classes of DBH, Ht, Hb, and WSG are illustrated in Figures 4A-4D. The number of tree samples in DBH classes of 10.0-15.0 cm, 15.1-20.0 cm, 20.1-25.0 cm, 25.1-30.0 cm, and 30.0-46.0 cm were 8, 11, 3, 4, and 4 trees, respectively. The DBH minimum of tree samples was 10.00 cm, while the DBH maximum was 45.20 cm. Most tree samples (73.33% or 22 trees) had DBH in the range of 10.00 cm to 24.07 cm, and only one tree sample with DBH between 38.16 cm and 45.20 cm. A 50-year-old secondary forest has more trees with small DBH because harvesters have commonly cut down the big DBH trees. The result of Sadono et al. (2021) study shows that, interestingly, the trend of biomass distribution in every part of the tree is relatively different across the increase of diameter classes.

The selected trees were dominated in the height range of 9.44 m to 13.07 m. Meanwhile, there were ten trees between 13.08 m and 16.70 m and only seven trees from 5.80 m to 9.43 m. The variation in tree height within a 50-year-old secondary forest contributes to its richness in bioresources, as trees can grow abundantly and in diverse sizes. A few tree samples were in the category Hb class between 8.34 m and 11 m, while others were in the 3.00-5.66 m and 5.67-8.33 m. In some instances, a tall tree may have a disproportionately large leaf canopy which can detract from its bole height. According to Sadono et al. (2021), biomass distribution in the stem could be higher than in other tree components. This is because it is the main tree component supporting the translocation process and maintaining tree stability. About 14 and 16 tree samples had high WSG of 0.27-0.34 g cm^{-3} and 0.35-0.58 g cm^{-3}, respectively.

Figure 3. A. The disc and branch samples were dried in an oven, B. The weighing of disk samples of the trunk fraction, C. The weighing of tree branch samples in the laboratory

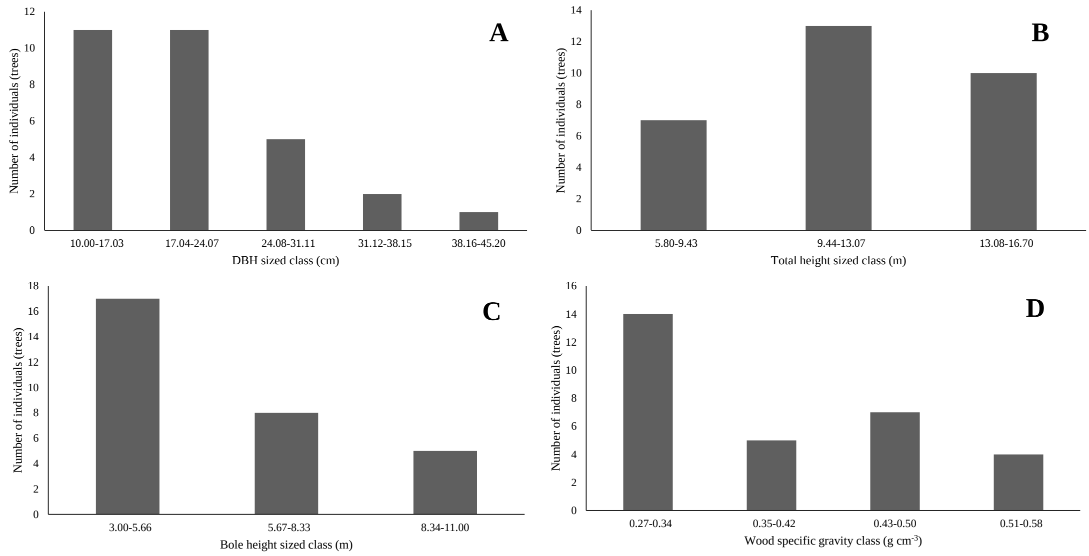

Figure 4. Number sample trees based on (A) DBH classes, (B) total height classes, (C) bole height classes, and (D) Wood Specific Gravity

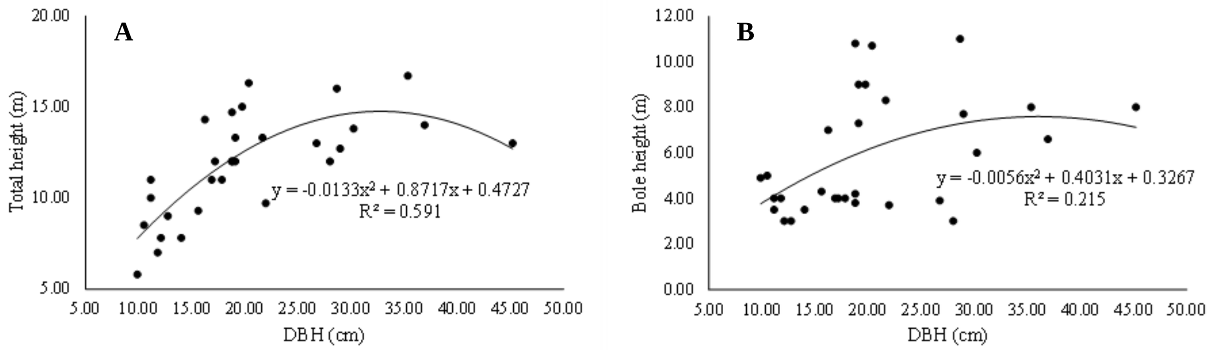

Figure 5. The relations between (A) DBH and total height, (B) DBH and bole height of tree samples

This study described the relationship between DBH and Ht, as well as DBH and Hb, in Figures 5A and 5B. This is supported by Mensah et al. (2018), where the tree height-diameter relationship facilitates biomonitoring and decision-making for sustaining and improving the ecological functions in natural forest systems. Furthermore, the relations between DBH and Ht are also explained by the equation $Ht = -0.0133DBH^2 + 0.8717DBH + 0.4727$ ($R^2 = 0.591$). A moderate relationship exists between DBH and Ht, where an increase of 59.1% in DBH will result in a corresponding increase in Ht. However, it should be noted that other variables influence 40.9% of the variation in Ht. The relation between DBH and Hb is $Hb = -0.0056DBH^2 + 0.4031DBH + 0.3267$ ($R^2 = 0.215$). This study found that the increase of DBH has weak relation with Hb. It is important to note that an increase in a tree's diameter does not necessarily correspond to an increase in stem height.

RESULTS AND DISCUSSION

Tree variables

Leaf, branch, trunk, and TAGB of selected tree samples ranged from 4.44-37.89 kg, 6.33-84.15 kg, 11.26 -145.34 kg, and 24.49-259.02 kg, respectively. The DBH, Ht, Hb, and WSG ranged from 9.87-45.20 cm, 5.80-16.70 m, 3.0-11.00 m, and 0.27-0.58 g cm^{-3}. Pearson correlations among DBH, Ht, Hb, WSG, leaf biomass, branch biomass, trunk biomass, TAGB, and destructive biomass parameters are presented in Table 1. The biomass of tree parts has a strong correlation with DBH and Ht ($P<0.01$), except for branch biomass and Ht ($P<0.05$). There was no correlation between leaf, branch, trunk, and total biomass on the Hb and WSG, except for the relations between trunk biomass and WSG ($P<0.05$). The absence of a correlation between leaf biomass with DBH and Ht also showed a similar relationship. The relations between the parameters showed that the correlation between DBH and Ht and WSG was very strong ($P<0.01$), while DBH and Hb were strong ($P<0.05$).

WSG is an important variable for estimating biomass, specifically for mixed tree species where the equation Log(TAG) =c + Log(DBH) + Log(WD) is the most appropriate in calculating the Total Above-Ground Biomass of mixed commercial tree species (Maulana 2014). Furthermore, the combination of diameter with height and diameter, height, and specific gravity of wood shows the highest adjusted R^2 values in the general equation (Pati et al. 2022).

The species of tree samples were selected to form the allometric equation based on the Important Value Index (IVI). The tree samples were the dominant and non-dominant species in the study plot, as reported by Karmini et al. (2021a). Selection considerations were also based on the representativeness of the DBH distribution. A total of 30 samples, representing 17 species from 13 genera belonging to 11 distinct families, were included in the study. The four tree samples were *A. elasticus* (Moraceae), as shown in Table 2. Furthermore, ten species were selected from two sample trees, while the other six were obtained from one sample tree each.

Table 1. Pearson's correlations between Diameter at Breast Height (DBH), total height, bole height, Wood Specific Gravity (WSG) and leaves biomass, branches biomass, trunk biomass, Total Above-Ground Biomass (TAGB), and parameters of destructive biomass

	Pearson's correlations (n=30)				Mean	Deviation	Range
	DBH (cm)	Total height (m)	Bole height (m)	Wood specific gravity (g cm^{-3})			
Leaf biomass (kg)	0.149^{ns}	0.252^{ns}	-0.131^{ns}	0.111^{ns}	13.45	10.21	4.44 - 37.89
Branch biomass (kg)	0.530**	0.422*	0.088^{ns}	-0.126^{ns}	25.70	19.11	6.33 - 84.15
Trunk biomass (kg)	0.844**	0.557**	0.175^{ns}	-0.408*	61.18	40.02	11.26 - 145.34
TAGB (kg)	0.725**	0.525**	0.117^{ns}	-0.281^{ns}	100.33	62.71	24.49 - 259.02
DBH (cm)	1	0.635**	0.418*	-0.537**	20.51	8.62	9.87 - 45.20
Total height (m)	0.635**	1	0.735**	-0.515**	11.80	2.81	5.80 - 16.70
Bole height (m)	0.418*	0.735*	1	-0.572**	5.84	2.55	3.00 - 11.00
Wood Specific Gravity (g cm^{-3})	-0.537**	-0.515**	-0.572**	1	0.38	0.09	0.27 - 0.58

Note: DBH=Diameter at Breast Height, TAGB=Total Above-Ground Biomass, ^{ns} is not significant at the 0.05 level (P>0.05), * and ** Correlation are significant at the 0.05 and 0.01 level (2-tailed) respectively

Table 2. All data sets for developing allometric equations in 50 years-old secondary forest

Tree no.	Species	Family	DBH (cm)	Total height (m)	Bole height (m)	Leaves (kg)	Branches (kg)	Trunk (kg)	TAGB (kg)	WSG (g cm^{-3})
1	*Artocarpus elasticus*	Moraceae	36.92	14.00	6.60	11.24	33.67	120.55	165.46	0.30
2	*Artocarpus elasticus*	Moraceae	30.24	13.80	6.00	9.57	23.96	79.00	112.53	0.32
3	*Artocarpus elasticus*	Moraceae	45.20	13.00	8.00	8.97	51.03	145.34	205.34	0.30
4	*Artocarpus elasticus*	Moraceae	19.10	12.00	9.00	5.95	19.74	50.37	76.06	0.30
5	*Macaranga motleyana*	Euphorbiaceae	17.83	11.00	4.00	19.28	41.06	102.92	163.26	0.34
6	*Bridelia stipularis*	Phyllanthaceae	15.60	9.30	4.30	9.41	20.74	46.49	76.64	0.47
7	*Bridelia stipularis*	Phyllanthaceae	11.78	7.00	4.00	4.50	8.41	19.26	32.17	0.58
8	*Symplocos fasciculata*	Symplocaceae	21.96	9.70	3.70	13.71	15.54	39.65	68.90	0.35
9	*Symplocos fasciculata*	Symplocaceae	28.01	12.00	3.00	9.26	13.00	128.17	150.43	0.35
10	*Macaranga motleyana*	Euphorbiaceae	19.10	13.30	7.30	9.06	19.49	62.77	91.32	0.37
11	*Ficus septica*	Moraceae	18.78	12.00	4.20	6.47	9.09	57.55	73.11	0.43
12	*Ecclinusa ramiflora*	Sapotaceae	18.78	12.00	3.80	37.89	60.70	88.71	187.30	0.49
13	*Ecclinusa ramiflora*	Sapotaceae	16.23	14.30	7.00	34.52	44.18	64.18	142.88	0.45
14	*Alstonia scholaris*	Apocynaceae	18.78	14.70	10.80	5.93	6.33	24.90	37.16	0.30
15	*Elaeocarpus stipularis*	Elaeocarpaceae	20.37	16.30	10.70	13.06	27.75	71.51	112.32	0.36
16	*Mallotus paniculatus*	Euphorbiaceae	10.00	5.80	4.90	4.44	9.61	22.62	36.67	0.32
17	*Mallotus paniculatus*	Euphorbiaceae	17.19	12.00	4.00	20.56	31.69	52.29	104.54	0.34
18	*Macaranga gigantea*	Euphorbiaceae	21.65	13.30	8.30	12.05	21.29	51.38	84.72	0.30
19	*Macaranga gigantea*	Euphorbiaceae	19.74	15.00	9.00	14.16	21.47	49.57	85.20	0.30
20	*Macaranga tanarius*	Euphorbiaceae	26.74	13.00	3.90	35.58	64.58	130.61	230.77	0.28
21	*Vernonia arborea*	Asteraceae	35.33	16.70	8.00	33.76	84.15	141.11	259.02	0.36
22	*Vernonia arborea*	Asteraceae	28.97	12.70	7.70	7.03	23.81	75.69	106.53	0.33
23	*Artocarpus tamaran*	Moraceae	28.65	16.00	11.00	4.78	16.53	59.26	80.57	0.27
24	*Artocarpus dadah*	Moraceae	16.87	11.00	4.00	9.74	14.45	24.46	48.65	0.44
25	*Artocarpus dadah*	Moraceae	11.14	10.00	3.50	4.70	8.71	16.39	29.80	0.44
26	*Artocarpus tamaran*	Moraceae	10.50	8.50	5.00	4.50	8.73	11.26	24.49	0.28
27	*Rhodamnia* sp.	Myrtaceae	12.73	9.00	3.00	9.36	11.65	24.82	45.83	0.47
28	*Vitex pinnata*	Lamiaceae	11.14	11.00	4.00	4.78	8.32	19.18	32.28	0.52
29	*Nauclea xanthoxylon*	Rubiaceae	14.01	7.80	3.50	27.36	35.86	36.03	99.25	0.53
30	*Nauclea xanthoxylon*	Rubiaceae	12.10	7.80	3.00	11.89	15.41	19.33	46.63	0.53
	Average		20.51	11.80	5.84	13.45	25.70	61.18	100.33	0.38
	Minimum		10.00	5.80	3.00	4.44	6.33	11.26	24.49	0.27
	Maximum		45.20	16.70	11.00	37.89	84.15	145.34	259.02	0.58
	Standard deviation		8.62	2.81	2.55	10.21	19.11	40.02	62.71	0.09

Note: DBH: Diameter at Breast Height, TAGB: Total Above-Ground Biomass, WSG: Wood Specific Gravity

Moreover, many tree species tend to have structure and physiognomy differently based on growth, stratification, and canopy cover (Karyati et al. 2019a). This will cause a difference in the biomass of tree parts or total biomass. The largest tree sample was *A. elasticus* (DBH 45.20 cm), with a trunk biomass of 145.34 kg. The tree sample with the largest total biomass (259.02 kg) was *Vernonia arborea* (DBH=35.33 cm), with a total height of 16.70 m. *Mallotus paniculatus,* with a DBH of 10.0 cm, exhibited the lowest biomass among the sample trees and displayed the smallest leaf biomass of 4.44 kg.

The developed allometric equations

This study developed equations for some tree parts, such as dry leaf biomass, dry branch biomass, dry trunk biomass, and above-ground dry biomass. The equations will be useful to support the more specific policy in forest management projects. Meanwhile, the carbon pool should be measured and monitored for various forest carbon projects (Sutaryo 2009). Furthermore, as demonstrated by Sutaryo (2009), initiatives aimed at mitigating emissions, such as the cessation of deforestation, the implementation of reduced-impact logging practices, and the enhancement of forest management protocols, may necessitate the measurement of live trees and dead rough biomass. Therefore, assessing live tree biomass and smooth dry biomass may also be required.

The allometric equations were developed to predict the biomass of the tree subject parts in the study plot shown in Table 3. The analysis of the equations on tree dimensions such as DBH, ($DBH^2×Ht$), ($DBH^2×Hb$), Ht, and Hb as independent variables with biomass leaves and branches as dependent variables, showed very weak relation. However, there is a relationship between total height (Ht) and bole height (Hb) on trunk biomass and total biomass above-ground level (TAGB). The adj R^2 value showed that the fluctuation in the independent variables and other factors causes the dry trunk and above-ground biomass variation. However, a low adj R^2 could be obtained due to the diversity of data. Although this study reported some adj R^2 values as low, testing the overall significance of all equations showed that most *F* values were very significant. The results rejected the null hypothesis that equators have no impact on the equation, even though adj R^2 is only < 0.8 (Table 3). According to Gujarati and Porter (2009), the model is correctly specified since the regressors have the correct signs as theoretically expected, and regression coefficients are statistically significant.

The tree dimensions and trunk biomass had the highest adj R^2 values of 0.641. Meanwhile, the highest value of adj R^2 in testing the relationship between tree dimensions and TAGB was 0.516. The relationships between tree dimensions and Total Above-Ground Biomass were very significant (P<0.001), except that the relations between Hb and total biomass were not significant (P>0.05).

Table 3. The developed allometric equations for predicting plant part biomass of subject trees in the study plot

Dependent variable (y)	Independent variable (x)	Equation symbol	Equation	*P*	Adj R^2	*F*	MSE	RMSE	MAPE	AIC
Leaf dry biomass (kg)	DBH (cm)	L1	$y = 7.504\ x^{0.017}$	>0.05	0.01	0.398ns	131.422	11.464	0.451	140.482
	($DBH^2×Ht$) (cm^2 m)	L2	$y = 9.486\ x^{0.001}$	>0.05	-0.01	-0,139ns	115.761	10.759	0.492	123.741
	($DBH^2×Hb$) (cm^2 m)	L3	$y = 10.395\ x^{0.001}$	>0.05	-0.03	-0,921ns	109.545	10.466	0.550	117.097
	Ht (m)	L4	$y = 4.662\ x^{0.070}$	>0.05	0.05	1,567ns	162.951	12.765	0.446	174.184
	Hb (m)	L5	$y = 12.830\ x^{-0.032}$	>0.05	-0.02	-0,576ns	102.037	10.101	0.668	109.071
Branch dry biomass (kg)	DBH (cm)	B1	$y = 8.131\ x^{0.045}$	<0.001	0.29	11,216**	619.130	24.882	0.487	661.813
	($DBH^2×Ht$) (cm^2 m)	B2	$y = 13.974\ x^{0.001}$	<0.01	0.26	10,043**	487.382	22.077	0.485	520.982
	($DBH^2×Hb$) (cm^2 m)	B3	$y = 15.364\ x^{0.001}$	<0.05	0.18	6,022*	457.051	21.379	0.498	488.560
	Ht (m)	B4	$y = 5.699\ x^{0.108}$	<0.05	0.16	5,493*	683.992	26.153	0.565	731.146
	Hb (m)	B5	$y = 16.705\ x^{0.034}$	>0.05	-0.02	-0,549ns	415.971	20.395	0.540	444.648
Trunk dry biomass (kg)	DBH (cm)	T1	$y = 12.356\ x^{0.067}$	<0.001	0.64	49,994**	3,649.757	60.413	0.629	3,901.368
	($DBH^2×Ht$) (cm^2 m)	T2	$y = 28.850\ x^{0.001}$	<0.001	0.52	29,971**	2,576.160	50.756	0.548	2,753.758
	($DBH^2×Hb$) (cm^2 m)	T3	$y = 32.940\ x^{0.001}$	<0.001	0.36	15,614**	2,329.806	48.268	0.569	2,490.420
	Ht (m)	T4	$y = 7.238\ x^{0.162}$	<0.001	0.39	17,528**	4,072.009	63.812	0.723	4,352.730
	Hb (m)	T5	$y = 31.594\ x^{0.074}$	>0.05	0.04	1,106ns	2,176.772	46.656	0.572	2,326.836
Above-ground biomass (kg)	DBH (cm)	A1	$y = 26.475\ x^{0.055}$	<0.001	0.52	29,851**	8,529.416	92.355	0.558	9,117.426
	($DBH^2×Ht$) (cm^2 m)	A2	$y = 53.279\ x^{0.001}$	<0.001	0.42	20,276**	5,969.003	77.259	0.511	6,380.500
	($DBH^2×Hb$) (cm^2 m)	A3	$y = 60.113\ x^{0.001}$	<0.01	0.27	10,251**	5,377.794	73.333	0.525	5,748.534
	Ht (m)	A4	$y = 16.897\ x^{0.134}$	<0.001	0.31	12,580**	9,663.045	98.301	0.656	10,329.207
	Hb (m)	A5	$y = 63.060\ x^{0.046}$	>0.05	-0.01	-0,056ns	4,816.068	69.398	0.534	5,148.083

Note: *P* values of the equation, coefficient of determination (R^2), Mean Square Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and Akaike's Information Criterion (AIC), Diameter at Breast Height (DBH), total tree height (Ht), bole tree height (Hb), ^{ns} is not significant at the 0.05 level (P>0.05), * and **correlation are significant at the 0.05 and 0.01 level (2-tailed) respectively

Total Above-Ground Biomass is the sum of leaf, branch, and trunk-dry biomass, as shown in Figure 6. The average TAGB of sampled trees in a 50-year-old secondary forest in East Kalimantan was 100.33 kg per tree (Table 2). The biggest biomass content at 61% of TAGB was approximately 61.18 kg per tree in the trunk. The mean biomass content in branches reached 25.70 kg per tree or 26% of TAGB. The small biomass content at 13% of TAGB could be found in leaves at an average of 13.45 kg per tree. This result is similar to Ohorella and Kaliky's (2011) finding, where the biggest biomass content is in the trunk of agroforestry plants but in a lower percentage of 52%. The trunk is the woody part and becomes the saving place for photosynthesis products that used to grow vertically to height and horizontally to diameter. Meanwhile, leaves are the primary site of photosynthesis, and the resulting products are transported to other parts of the tree. Leaves have higher proteins than cellulose, making the decomposition process faster than the trunk, which has higher cellulose and hemicellulose (Ohorella and Kaliky 2011).

The selected allometric equations

The chosen allometric equations utilized for estimating tree component biomass within the study plot are presented in Table 4. This study selected 4 of 20 allometric equations ([L4], [B1], [T1], and [A1]) to estimate the tree part biomass when the independent variables are Ht or DBH. Figure 7 is the graphs of some equations which consist of a close relationship among tree dimensions, trunk biomass, and above-ground biomass. There are variations in MSE, RMSE, MAPE, and AIC. However, the selected equations display similarities, as each tested group features the highest Adj R^2 value from 0.053 to 0.641.

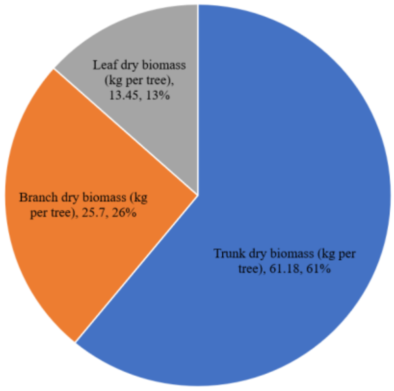

Figure 6. The average dry leaf biomass, dry branch biomass, and dry trunk biomass per tree in the study site

Table 4. The selected allometric equations for predicting plant part biomass of subject trees in the study plot

Dependent variable (y)	Independent variable (x)	Equation symbol	Equation	*P*	Adj R^2	MSE	RMSE	MAPE	AIC
Leaf dry biomass (kg)	Ht (m)	[L4]	$y = 4.662\ x^{0.070}$	0.11591488	0.053	162.951	12.765	0.446	174.184
Branch dry biomass (kg)	DBH (cm)	[B1]	$y = 8.131\ x^{0.045}$	0.00137097	0.286	619.130	24.882	0.487	661.813
Trunk dry biomass (kg)	DBH (cm)	[T1]	$y = 12.356\ x^{0.067}$	0.00000006	0.641	3,649.757	60.413	0.629	3,901.368
Above-ground biomass (kg)	DBH (cm)	[A1]	$y = 26.475\ x^{0.055}$	0.00000469	0.516	8,529.416	2.355	0.558	9,117.426

Note: coefficient of determination (R^2), Mean Square Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Akaike's Information Criterion (AIC), total tree height (Ht), Diameter at Breast Height (DBH)

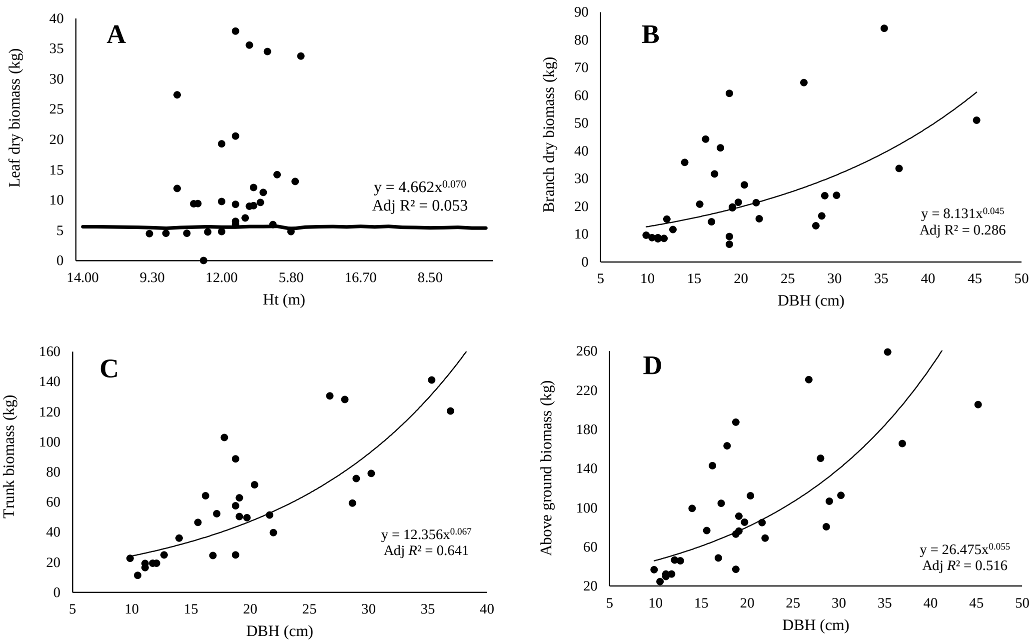

Figure 7. The selected equations of 50 years-old secondary forest

A significant correlation was shown by the mixed species allometric equation relating AGB and diameter to stump height (R^2=0.78; P<0.01) and tree height (R^2=0.41, P<0.05) (Mokria et al. 2018). A strong correlation (Adj R^2=0.59-0.95) was shown by the relations between dry stem biomass and AGB at breast height diameter (DBH) and height in secondary forests with different ages of 5, 10, and 20 years after abandonment. The correlation between dry leaf, branch biomass, and tree height was relatively weak (Adj R^2=0.36-0.50) (Karyati et al. 2019b). A very weak relationship between leaf and branch dry biomass of trees and plant dimensions was reported after shifting cultivation. Furthermore, the developed allometric equation shows a relatively low R^2 (<0.60) (Karyati et al. 2019a). The relations between stem biomass, AGB, and the dimensions of the trees in the abandoned traditional gardens are very strong, indicated by the relatively high value of Adj R^2. A fairly strong relationship was shown between branch biomass and tree dimensions, while the relation between leaf biomass and tree dimensions was very weak (Karyati et al. 2021). The allometric equations are built to estimate the biomass of plant parts in secondary forests where various types of plants grew. Disparities in plant species and individual specimens often result in variations in plant structure, physiognomy, and carbon content. In addition, the growth of different trees varies at the species level and certain characteristics based on site conditions (Parlucha et al. 2017).

Comparison among various allometric equations

The AGB and carbon stock estimation using various allometric equations reported in some articles are presented in Table 5. AGB estimation using selected allometric equations at the study site and carbon stock ranged from 27.67 to 103.00 Mg ha^{-1} and 13.84-51.50 Mg ha^{-1}. Meanwhile, the estimation of AGB and carbon stock by using the developed allometric equation is lower than the estimate using the values of Manuri et al. (2017) (103.00 and 51.50 Mg ha^{-1}), Kiyono and Hastaniah (2005) (94.74 and 47.37 Mg ha^{-1}), Karyati et al. (2019a) (76.07 and 38.04 Mg ha^{-1}), Kenzo et al. (2009) (58.06 and 29.03 Mg ha^{-1}), and Karyati et al. (2021) (52.48 and 26.24 Mg ha^{-1}). The equation of Karyati et al. (2019b) resulted in a smaller estimate of AGB (27.67 Mg ha^{-1}) and carbon stock (13.84 Mg ha^{-1}). A comparison of the various allometric relationships between AGB and DBH is shown in Figure 8.

Therefore, using several previous allometric equations to estimate biomass and carbon stock yields higher values than those developed at the study site. This is related to variations in the Wood Specific Gravity of the sample trees, which is a basic property of woody plants for exhibiting ecological and performance characteristics in plant communities. Wood density also determines tree and forest biomass in carbon cycle studies (Vieilledent et al. 2018), and pioneer species dominated the selected tree samples. Variations in tree samples cause variation to occur in Wood Specific Gravity, ranging from 0.27-0.58 cm g^{-3}. For species-specific equations, the combination of diameter and height predicts above-ground biomass more precisely than the diameter and wood density (Pati et al. 2022).

Using the developed allometric equation, the application of Kenzo et al. (2009) and Karyati et al. (2021) estimated AGB and similar carbon stocks. The wood density obtained using the equation of Kenzo et al. (2009) and Karyati et al. (2021) was 0.35 cm g^{-3} and 0.30 to 0.77 cm g^{-3}. A comparison of the wood density of the tree samples in the equations of Kiyono and Hastaniah (2005) is 0.67 cm g^{-3}. Kenzo et al. (2009) and Karyati et al. (2019a) reported allometric equations for mixed species in tropical Kalimantan forests with a wood density of 0.35 cm g^{-3} and 0.24-0.44 cm g^{-3}. Tree species influence the estimation of AGB, stand characteristics, wood density, and tree height. Meanwhile, the characteristics of the biogeographic area only have a small effect on the developed AGB equation (Manuri et al. 2017). The amount of tree biomass varies between regions determined by tree species density, climatic factors, and soil properties (Agevi et al. 2017).

This study develops allometric equations in 50 years-old secondary forests, particularly pioneer tree species with a history of land use after shifting cultivation, forest fires, and abandoned traditional gardens. The selection of an appropriate allometric equation will result in an accurate estimate of the biomass and carbon stock. The development of precise allometric equations for traditional gardens situated in the tropics is a complementary effort to the previously reported allometric equations. These equations are anticipated to offer alternative solutions for appropriate purposes and users.

Table 5. Estimation of AGB and carbon stock by using various reported relationships for trees

No.	Equation	Author	Estimate of AGB (Mg ha^{-1})	Estimate of C stock (Mg ha^{-1})
1	$AGB=0.1008DBH^{2.5264}$	Kiyono dan Hastaniah (2005)	94.74	47.37
2	$AGB=0.0829DBH^{2.43}$	Kenzo et al. (2009)	58.06	29.03
3	$AGB=0.071\times DBH^{2.667}$	Manuri et al. (2017)	103.00	51.50
4	$\ln(AGB)=2.3207\times\ln(DBH)-1.89$	Karyati et al. (2019a)	76.07	38.04
5	$\ln(AGB)=0.808\times\ln(DBH)+1.277$	Karyati et al. (2019b)	27.67	13.84
6	$\ln(AGB)=1.492\times\ln(DBH)+0.117$	Karyati et al. (2021)	52.48	26.24
Current study plot				
7	$ABG = 26.475\ DBH^{0.055}$		32.87	16.43

Note: AGB: above-ground biomass, C: carbon, DBH: Diameter at Breast Height (cm)

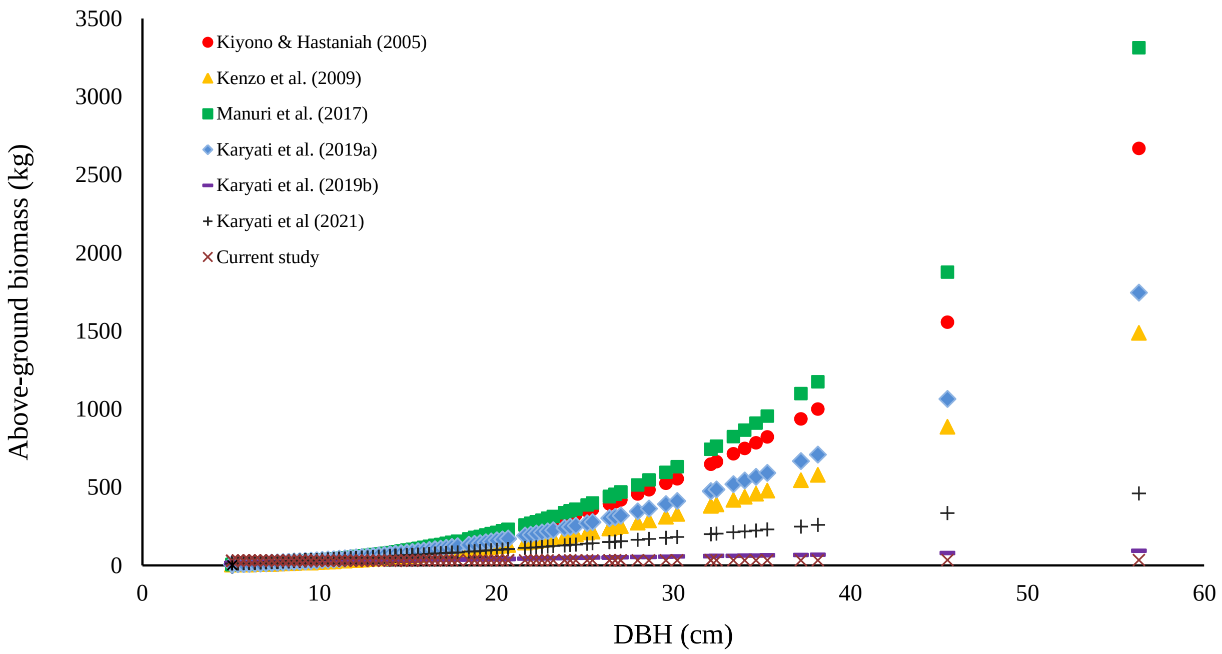

Figure 8. Comparison among various allometric relationships between Above-Ground Biomass (AGB) and Diameter at Breast Height (DBH) in the study site

In conclusion, the allometric equation can estimate tree trunk and above-ground tree biomass in the 50-year secondary forest using data on Diameter at Breast Height and a combination of DBH-tree height. Some of these equations have a fairly high significance compared to allometric equations for estimating leaf and branch biomass. The diversity of tree species, the history of land use, and the types of disturbance experienced by secondary forests during the succession process can influence the resulting allometric equations.

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