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Allometric equation for the biomass and carbon stock of cajuput (*Melaleuca cajuputi* Powell) stand in Wanagama Forest, Yogyakarta, Indonesia

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Abstract

Indonesia forests are ecosystems with mega biodiversity. Although many allometric equations have been developed for either forest types or tree species, a species–specific allometric equations are still important for precise estimation. The cajuput tree is a promising species that can provide non-timber forest products and mitigate climate change. In Indonesia, cajuput trees have been utilized as a source aromatic oil in forest plantations and natural forests. For climate change mitigation, cajuput could be useful as carbon stock. This research aimed to develop an allometric equation of naturally growing cajuput from Wanagama Forest using destructive sampling with 30 samples of cajuput trees to develop and 20 samples to validate the allometric equation. Power model law was used to develop the allometric equation. The requirement of the selected allometric equation was high coefficient determination (R^2_{adj}), low value of mean absolute bias, and low value of root mean square error. Results showed that and were the best allometric equations to estimate dry-weight biomass and carbon content, respectively. The predictor of diameter at breast height was robust in estimating the biomass and carbon of cajuput. Adding a predictor of total height did not significantly affect the allometric equation.

Key words: carbon accounting, climate change mitigation, non-timber forest products, teaching forest.

Introduction

Melaleuca forest is distributed in Australia and Southeast Asia, and is cultivated in other regions of the World, like Southern United States, and the Caribbean (Tran et al. 2013a). In Australia, the carbon stock of *Melaleuca* has not been reported adequately (Tran et al. 2013b). From an ecological perspective, the *Melaleuca* forest has potential for climate change mitigation (Tran et al. 2013a). However, less attention has been paid to the *Melaleuca* forest as carbon stock in Southeast Asia, such as Vietnam and Indonesia (Tran et al. 2015, Mulyana et al. 2021).

Melaleuca forest in Indonesia has been distributed in Maluku, Papua, and Java Island. Cajuput (*Melaleuca cajuputi* Powell) oil is well known in Indonesia as aromatic oil and is used in the traditional medicine. In Java Island, National Forestry Enterprise (Perhutani) and Forest Management Unit of Yogyakarta (KPH Yogyakarta) are the major producers of cajuput oil (Utomo et al. 2012; Mulyana et al. 2018, 2021) and own cajuput plantation and cajuput oil factory. In Maluku and Papua Island, cajuput grows naturally and is processed traditionally by the community around the cajuput forest (Parera et al. 2006; Widiyanto and Siarudin 2013, 2014; Siarudin and Widiyanto 2014). The species resources, both from natural stands and plantations has contributed significantly to the community economy (Parera et al. 2006, Indrajaya et al. 2013).

Cajuput trees play an essential role in the socio-economy and should be considered in climate change mitigation due to their ability to remove CO_2 from the atmosphere. Cajuput forest has a capacity to store carbon at around 169 ± 26 t $C{\cdot}ha^{-1}$ (aboveground) and 104 ±16 t $C{\cdot}ha^{-1}$ in soil and roots (Tran and Dargusch 2016). Specifically in Indonesia, the carbon stock of cajuput leaves/twigs in KPH Yogyakarta is 0.871 t $C{\cdot}ha^{-1}$ (Mulyana and Purwanto 2020). It is of particular interest to estimate the carbon stock of cajuput in natural forests because the characteristics of the species there differ from those in the plantations. For instance, the cajuput trees in Perhutani and KPH Yogyakarta have a similar height for all ages (around 1.5 m height), and the leaves/twigs are harvested periodically (approximately 9 months) (Utomo et al. 2012; Mulyana et al. 2019, 2021). The trees growing naturally in natural forests have complex diameter distribution and total height (Widiyanto and Siarudin 2013, 2014; Siarudin and Widiyanto 2014).

The cajuput plantation is one of the important source of products from KPH Yogyakarta. Meanwhile, naturally grown cajuput can be found in Forest with Special Purpose (Kawasan Hutan Dengan Tujuan Khusus/KHDTK) Wanagama in compartment 7. Mulyana et al. (2021) elaborated the use of allometric equation to estimate leaf/twig biomass in KPH Yogyakarta using three predictors, namely, height of the canopy, canopy diameter, and stem diameter. However, the accuracy is not satisfactory because of the low coefficient determination (0.428) and >1% aggregate deviation. Understanding cajuput allometry is crucial in estimating its potential as carbon stock or biomass energy source. The objective of the present study was to develop an allometric equation for estimating the biomass and carbon content of naturally grown cajuput stand in Wanagama Forest.

Material and Methods

Research site

Fieldwork was conducted in May 2021 at compartment 7 of Forest with Special Purpose (Kawasan Hutan Dengan Tujuan Khusus/KHDTK*)* of Wanagama (hereinafter called as Wanagama Forest, Yogyakarta). Wanagama Forest is located in Gunungkidul District, Province of Special Purpose Yogyakarta (Fig. 1). Compartment 7 is dominated by cajuput (*Melaleuca cajuputi*), gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.), mixed forest, and shrub. The land use of compartment 7 consists of cajuput (23.4 ha), gliricidia (17.0 ha), shrub (14.2 ha), and mixed forest (9.0 ha).

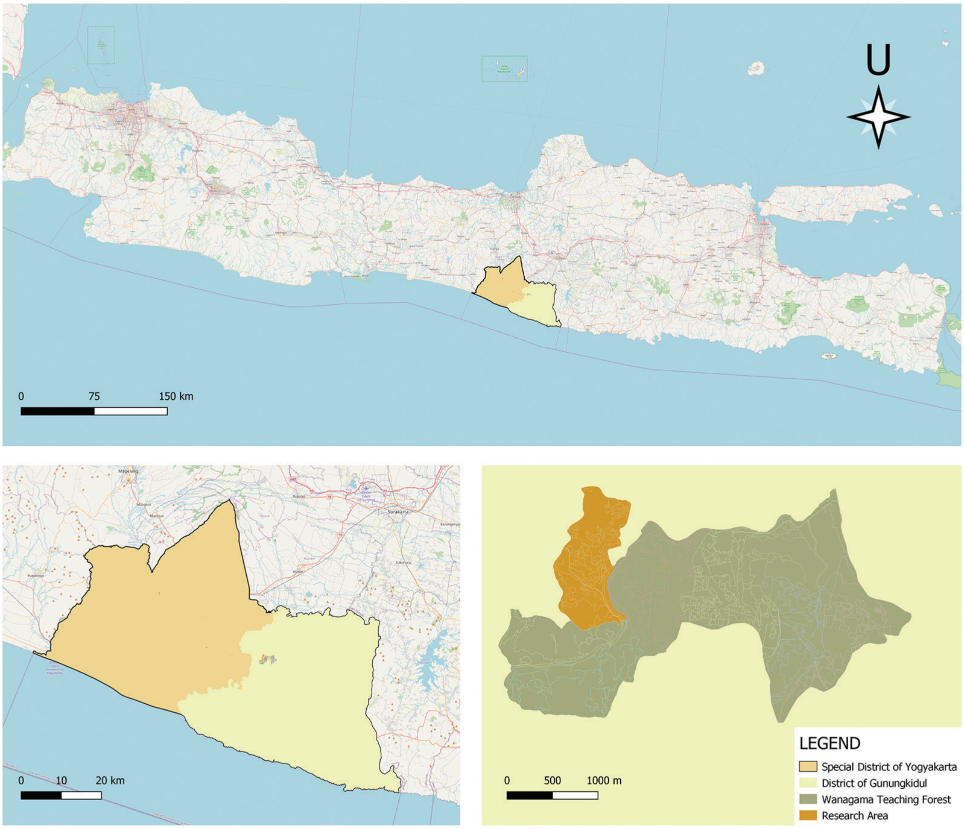

Fig. 1. Research site.

The cajuput stands in compartment 7 of Wanagama Forest were planted and grown naturally without specific treatments. This condition differed for the cajuput stands in Perhutani and KPH Yogyakarta, which were harvested at the height of around 1.5 m to utilize the leaves/twigs (Utomo et al. 2012, Mulyana et al. 2019). Utomo et al. (2012) and Mulyana et al. (2019) explained that the leaves and twigs of cajuput are harvested every year because of cajuput's ability to regenerate.

Data collection

Fifty cajuput trees were divided into two groups, namely, a sample set to develop an allometric equation (30 samples) and a sample set to validate the allometric equation (20 samples). Purposive sampling was used for the determining of selected samples. The selection was based on diameter distribution, accessibility of tree locations, and healthy conditions of the trees.

The selected samples were harvested at the height of 1.5 m, and the cut trees were divided into stems, branches, and leaves/twigs. In the future, the remaining cajuput stump can still produce new leaves/twigs that can be utilized for cajuput oil production (Utomo et al. 2012, Mulyana et al. 2019). Utomo et al. (2012) and Mulyana et al. (2019) described that the cajuput can produce leaves/twigs for

40 years.

The fallen sample trees were measured for their total height. Each section was weighed for the fresh-cut biomass using 0.001 kg precision digital scales. For the total stem biomass, the weight of fallen stem biomass and the biomass of the remaining stump were summed up. The remaining stumps were measured for the diameter at the base (D_b), diameter at the tip (D_t), and height of the stump (h). Volume (v) was then calculated (Fig. 2). The stem biomass was estimated using the equations (1–3) as follows:

$$V = \frac{D_b + D_t}{2} \cdot h, \tag{1}$$

$$B = V \cdot W_d, \tag{2}$$

$$H = h + h', \tag{3}$$

where: V is the volume, cm^3; D_b is the diameter at base, cm; D_t is the diameter at tip, cm; B is the biomass, g; W_d is the wood density, g/cm^3; h is the height of stump, cm; h' is the height of fallen cajuput sample, cm; and H is the total height of cajuput tree, cm.

The fresh-cut samples of wood, branches, and leaves were dried in the oven. According to Indonesia National Standard (SNI) No. 7724 about the measurement and calculation of carbon stock, the samples of stems and branches for oven drying must have at least 2 cm width and a disk shape. The minimum amount of leaves for drying was 100 g. The samples were dried in the oven at 70–85 °C for 72 hours until they reached a stable weight (Badan Standarisasi Nasional 2011).

Data analysis

The allometric models of dry-weight biomass and carbon stock of cajuput stand were developed from destructive sampling data and estimated using a single predictor (diameter or height) and two predictors (diameter and height). The power model is an allometric equation commonly used to estimate biomass and carbon and has been widely applied in mangrove forests (Ong et al. 2004, Kusmana et al. 2018), forest plantations (For-

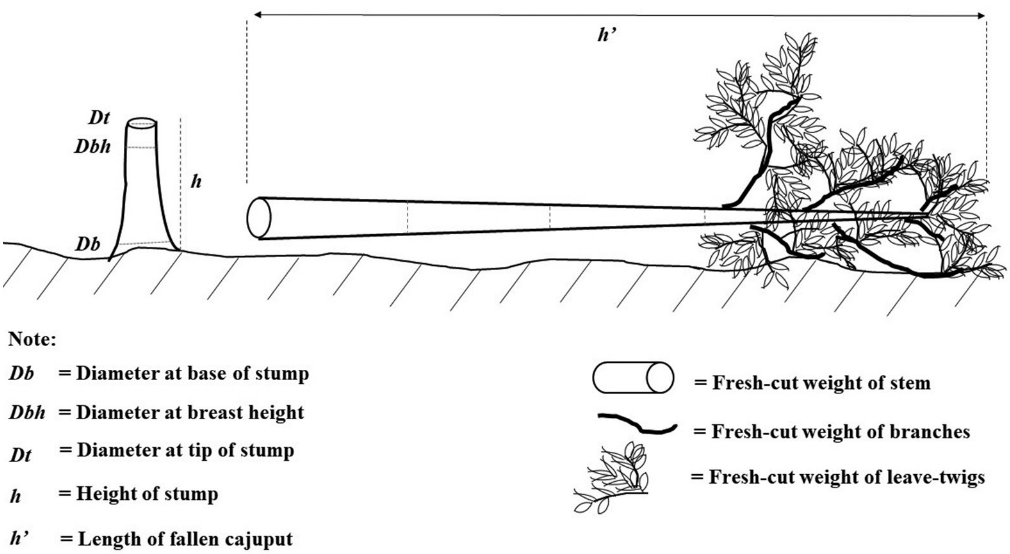

Fig. 2. Data collection of cajuput biomass.

tier et al. 2017, Mulyana et al. 2020). We evaluated the extent to which general or site-specific allometric equations, using diameter at breast height (DBH, dryland forests (Almulqu et al. 2019), and community forest (Wirabuana et al. 2021). Following the methods of Fortier et al. (2017) using diameter at breast height (DBH and Wirabuana et al. (2021), the simple power equations (4–6) to estimate biomass and carbon were as follows:

$$Y = \beta_0 \cdot D^{\beta_1}, \tag{4}$$

$$Y = \beta_0 \cdot H^{\beta_1}, \tag{5}$$

$$Y = \beta_0 \left(D^2 \cdot H\right)^{\beta_1}, \tag{6}$$

where: Y is the dry-weight biomass or total carbon, kg; D is the diameter, cm; H is the total height, m; and β_0 and β_1 are intercepts.

According to Lukito (2011), the average percentage carbon content (*PCC*) of cajuput was 67.53% in stems, 66.40% in branches, and 59.41 % in leaves. The dry-weight biomass was converted to carbon content using the calculated total carbon content in equation (7).

$$TC = \left(0.675 \cdot DW_s\right) + \left(0.664 \cdot DW_b\right) + + (0.594 \cdot DW_l), \tag{7}$$

where: TC is the total carbon, kg; DW_s is the stem dry-weight, kg; DW_b is the branches dry-weight, kg; DW_l is the leave dry-weight, kg.

Biomass (dependent variable) was estimated using the predictors (independent variables) of diameter at breast height (D), total height (H), and the combination of diameter at breast height with total height ($D^2 \cdot H$). The best model was chosen based on the highest value of adjusted coefficient determination (R^2_{adj}) and the lowest values of root mean square error (RMSE) and mean absolute bias (MAB). These parameters can describe the bias between the observed and predicted values (Wirabuana et al. 2021). The equations (8–9) for MAB and RMSE were as follows:

$$MAB = \frac{\sum_{i=1}^{n} \left| Y - \overline{Y} \right|}{n}, \tag{8}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(\left| Y - \overline{Y} \right| \right)^2}{n}} \tag{9}$$

where: *MAB* is the mean absolute bias, *RMSE* is the root mean square error, Y is the observed value, and is the predicted value.

The validation of the allometric equation is important in assessing the ability of the model to predict the biomass or carbon based on the selected predictor. This step must be conducted using a dataset differing from the one used in the development of allometric equations (Mulyana et al. 2020). In a small sample size, leave-one-out cross-validation can be applied to process the validation test (Wirabuana et al. 2021). The bias between the observed and predicted values can be analyzed using MAB and RMSE.

Results and Discussion

Statistic summary of cajuput samples

The total aboveground biomass of naturally grown cajuput in Wanagama Forest was allocated in the stems, branches, and leaves/twigs. The dominant biomass allocation was in the stem section, followed by the branches and leaves/twigs (Fig. 3). A similar biomass allocation was also found in the cajuput plantation at Perhutani, in which the aboveground biomass was distributed in the stems (69.44 %), branches (10.27 %), and leaves/twigs (20.29 %) (Lukito 2011).

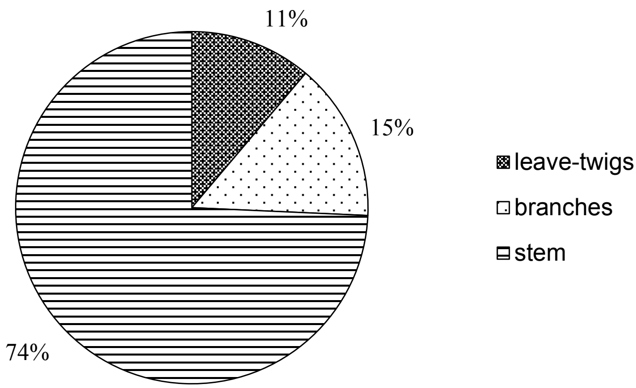

Fig. 3. Biomass allocation in cajuput tree.

A comprehensive research also found dominant stem biomass in the cajuput stand in a peat swamp forest in Indonesia, where the biomass was distributed in the stems (57.69%), roots (22.21 %), branches (17.94 %), leaves (1.35 %), flowers (0.16 %), and fruits (0.66 %) (Alpian et al. 2013). Therefore, the wide range of habitat of cajuput and the site quality could affect its growth and biomass distribution.

The cajuput samples used in developing an allometric equation (Table 1) had similar characteristics to those used in validating the allometric equation (Table 2). In general, the samples represented the real condition of the cajuput stand in Wanagama Forest. The average diameter at breast height of all cajuput samples (data set for development and validation) was 7.4 cm, and the total height average was 7.42 m.

Biomass (dependent variable) was estimated using the predictors (independent variables) of diameter at breast height (D), total height (H), and the combination of diameter at breast height with total height ($D^2 \cdot H$). The relationship of the total dry-weight of cajuput with the stem diameter, total height, and combination of diameter and total height exhibited a non-linear regression pattern (Fig. 4). This trend was similar to that in *Gliricidia sepium*

Table 1. Statistic summary of the measurements of cajuput samples to develop the allometric equation.

Variables	Minimum	Maximum	Average	Standard deviation
Diameter at breast height, cm	3.90	10.50	7.28	1.55
Total height, m	4.69	13.00	7.47	2.06
Fresh-cut weight of stem, kg per tree	3.20	54.05	20.60	11.01
Fresh-cut weight of branch, kg per tree	0.56	6.90	2.96	1.71
Fresh-cut weight of leave, kg per tree	0.64	9.70	3.07	1.87

Table 2. Statistic summary of the measurements of cajuput samples to validate the allometric equation.

Variables	Minimum	Maximum	Average	Standard deviation
Diameter at breast height, cm	3.60	12.40	6.90	1.99
Total height, m	3.60	9.20	7.17	1.15
Fresh-cut weight of stem, kg per tree	2.28	28.0	25.12	11.04
Fresh-cut weight of branch, kg per tree	0.25	7.98	1.88	1.77
Fresh-cut weight of leave, kg per tree	0.40	6.05	2.06	1.54

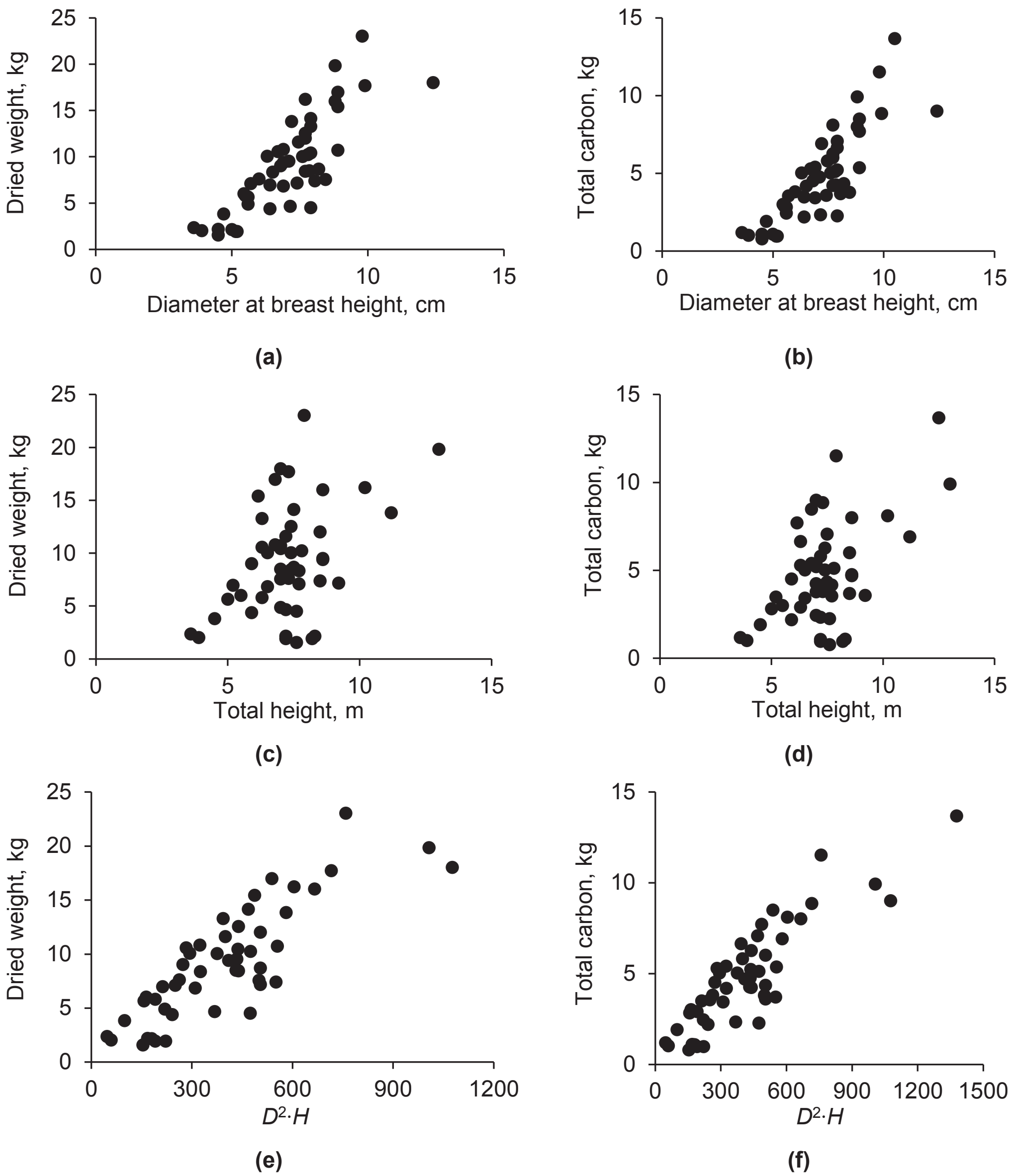

Fig. 4. Relationship among dried biomass (a, c, e) and total carbon (b, d, f) as dependent variables and diameter at breast height (*D*), total height (*H*), and combination of the two ($D^2 \cdot H$).

(Mulyana et al. 2020), *Ziziphus mauritiana* Lam. (Kurniawan and Pujiono 2019) but differed from that in cajuput trees in KPH Yogyakarta (Mulyana et al. 2021). Thus, the allometric equation of naturally grown cajuput in Wanagama Forest can be compared with other species due to their similar characteristics. However, the allometric equation is not suitable for comparing the naturally growing cajuput in Wanagama Forest with the utilized cajuput in forest plantation.

Specific allometric equation for estimating dry-weight biomass in Indonesia

Allometric equations for estimating biomass and carbon have been applied in many forest types in Indonesia. For instance, Yamakura et al. (1986) developed an allometric equation in the tropical rain forest, Basuki et al. (2009)so far the equations for Dipterocarp forests have not been developed in sufficient detail. In this research, allometric equations are presented based on the genera of commercial species and mixed species. Separate equations are developed for the Dipterocarpus, Hopea, Palaquium and Shorea genera, and an equation of a mix of these genera represents commercial species. The mixed species is constructed from commercial and non-commercial species. The data were collected in lowland mixed Dipterocarp forests in East Kalimantan, Indonesia. The number of trees sampled in this research was 122, with diameters (1.30 m or above buttresses in tropical lowland dipterocarp forest at East Kalimantan, Maulana (2014) in Papua tropical forest, Almulqu et al. (2019) in dryland forest at East Nusa Tenggara, and Wirabuana et al. (2021) in community forest at Java. In addition, Kusmana et al. (2018) developed species–specific allometric equations for *Sonneratia* sp. in the mangrove forest, Mulyana et al. (2020) for *Gliricidia sepium* in bioenergy plantation, and Akbar (2012) for *Shorea teysmanniana* Dyer ex Brandis in peat swamp forest. Indonesia's forest biodiversity, either forest type or species, is enormous. Nevertheless, the allometric equations for specific forest types or sites and species must be further developed to eliminate under- or overestimation (Manuri et al. 2017) biogeographical zones and various succession and degradation levels of natural lowland forests in the Indo-Malay region. The only additional variable that significantly and largely contributed to explaining AGB variation is grouping based on wood-density classes. Context: There is a need for an AGB equation at tree level for the lowland tropical forests of the Indo-Malay region. In this respect, the influence of geographical, climatic and ecological gradients needs to be assessed. Aims: The overall aim of this research is to provide a regional-scale analysis of allometric models for tree AGB of lowland tropical forests in the Indo-Malay region. Methods: A dataset of 1300 harvested trees (5 cm ≤ trunk diameter ≤ 172 cm.

The power model in this research showed an excellent performance in estimating biomass and carbon using the predictors of diameter at breast height and combination of diameter and height. The coefficient of determination (R^2_{adj}) was similar for the allometric equations, but the values of intercept (β_0 and β_1) differed (Table 3). The intercept of β_0 in the allometric equation for estimating total carbon was lower than that in the allometric equation for estimating dry-weight biomass. This finding can be explained by the PCC of cajuput at around 59%–67% from dry-weight biomass.

According to Table 3, the predictors of diameter and combination of diameter and height can be considered as the best allometric equations. The allometric equations for estimating the dry-weight biomass and carbon content of cajuput were

Table 3. Allometric equations for estimating dry-weight biomass and carbon content.

Variables	Equation	β_0	β_1	R^2_{adj}	SEE	$p <$
Dry-weight biomass	$DW = \beta_0 \cdot D^{\beta_1}$	0.136	2.190	0.935	0.181	0.001
	$DW = \beta_0 \cdot H^{\beta_1}$	0.260	1.872	0.559	0.472	0.001
	$DW = \beta_0 \left(D^2 H\right)^{\beta_1}$	0.084	0.813	0.942	0.171	0.001
Total carbon	$C = \beta_0 \cdot D^{\beta_1}$	0.142	1.951	0.912	0.211	0.001
	$C = \beta_0 \cdot H^{\beta_1}$	0.258	1.641	0.609	0.369	0.001
	$C = \beta_0 \left(D^2 H\right)^{\beta_1}$	0.054	0.817	0.945	0.161	0.001

Note: *DW* is dry-weight biomass, kg; *C* is total carbon, kg; *D* is the diameter at breast height, cm; and *H* is the total height, m.

$DW = 0.136 D^{2.190}$ and $C = 0.142 D^{1.951}$, respectively. Both allometric equations showed a coefficient of determination above 0.900. A strong correlation was found between dry aboveground biomass or total carbon and the predictor of diameter at breast height.

The findings also confirmed previous works on existing allometric equations in Indonesia stating that biomass and carbon can be estimated using the diameter as predictor in the power model (Table 4). For the cajuput stand, which lives in the peat swamp forest in Indonesia, the power model can be used to estimate dry biomass using the predictor of diameter at breast height. However, the allometric equation for mixed species showed a lower coefficient of correlation than that for the single species.

Table 4. Summary of the existing allometric equations in Indonesia.

Species	Forest type	Equation	R^2_{adj}	References
Melaleuca cajuputi	Peat swamp	$DW = 0.128 \cdot \mathrm{DBH}^{2.410}$	0.994	Alpian et al. (2013)
Sonneratia sp.	Mangrove	$DW = 0.299 \cdot \mathrm{DBH}^{2.300}$	0.950	Kusmana et al. (2018)
Gliricidia sepium	Forest plantation	$C = 0.019 \cdot D_{30}{}^{2.719}$	0.958	Mulyana et al. (2020)
Shorea teysmanniana	Peat swamp	$DW = 0.09 \cdot \mathrm{DBH}^{2.58}$	0.990	Akbar (2012)
Acacia nilotica L.	Savanna	$DW = 0.340 \cdot \mathrm{DBH}^{1.970}$	0.984	Istomo and Farida (2017)
Ziziphus mauritiana	Savanna	$DW = 50.75 \cdot \mathrm{DBH}^{2.350}$	0.959	Kurniawan and Pujiono (2019)
Mixed stands	Lowland dipterocarp forest	$DW = 0.125 \cdot \mathrm{DBH}^{2.533}$	0.821	Manuri et al. (2016)

Note: *DW* is dry-weight biomass, kg; *C* is total carbon, kg; DBH is the diameter at breast height, cm; and D_{30} in cm is the diameter at 30 cm from the base.

Meanwhile, the predictor of total height (H) showed a weak correlation with the dry-weight (R^2_{adj} = 0.559, p < 0.001) or total carbon (R^2_{adj} = 0.559, p < 0.001) of cajuput. Statistical analysis also showed poorer, although significant correlation between diameter at breast height and total height (R^2_{adj} = 0.678, p < 0.001). This finding differed from the studies on Poplar species, in which the diameter at breast height had a strong correlation with total height (R^2 = 0.820, p < 0.001) (Fortier et al. 2017)using diameter at breast height (DBH. Owing to the unique characteristics of each species, the allometric equation must be species–specific.

The cajuput tree in Yogyakarta has unique characteristics. This research showed that the diameter at breast height posesses a low correlation with the total height. In addition, the crown dimension of cajuput could not accurately predict its biomass (Mulyana et al. 2021). Elaborating the allometric equation is still important in estimating cajuput biomass.

Validation of cajuput allometric equation

The allometric equation with predictor diameter and combination diameter and height produced high coefficients of determination (R^2_{adj}) and the predictor diameter showed the lowest bias (Table 5). By contrast, the total height predictor did not precisely estimate the biomass or carbon.

The use of a single predictor of diameter is highly efficient for fieldwork or rapid assessment. Total height is relatively difficult to estimate, and diameter can be measured easily and precisely (Tiryana 2016). Wirabuana et al. (2020) also recommended using the diameter as a predictor of tree biomass in community forests because of its lower variance than total tree height in the same area. Adding the predictor height did not contribute significantly to the allometric equation, either for dry-weight or carbon content estimation.

Table 5. The allometric equation to estimate carbon stock.

Variables	Equation	MAB	RMSE
Dry-weight biomass	$DW = \beta_0 D^{\beta_1}$	2.974	3.358
	$DW = \beta_0 H^{\beta_1}$	3.180	3.542
	$DW = \beta_0 \left(D^2 H\right)^{\beta}$	3.561	3.981
Total carbon	$C = \beta_0 D^{\beta_1}$	2.793	2.995
	$C = \beta_0 H^{\beta_1}$	2.785	2.929
	$C = \beta_0 \left(D^2 H\right)^{\beta_1}$	3.158	3.418

Note: *DW* is dry-weight biomass, kg; *C* is total carbon, kg; *D* is the diameter at breast height, cm; *H* is the total height, m; MAB is mean absolute bias; and RMSE is the root mean square error.

Conclusion

Diameter at breast height is the best predictor to estimate the dry-weight and carbon content of cajuput in Wanagama Forest. The allometric equations for estimating the dry-weight and carbon content of cajuput were $DW = 0.136 \cdot D^{2.190}$ and $C = 0.142 \cdot D^{1.951}$.

Recommendation

This research was conducted in marginal land, in which the soil formation was dominated by limestone and low water input. Further research on the allometric equation of cajuput can be performed in other types of forest ecosystems, such as dryland, savanna, and tropical rain forest in Indonesia. It will allow development of a comprehensive cajuput allometric equation, which can be applied to a wide range of forest ecosystems in Indonesia.

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