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CASE STUDY

Allometric equations model for estimating an above and below ground biomass of dipterocarp forest in the tropics

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ABSTRACT

BACKGROUND AND OBJECTIVES: Accurate measurement of carbon stocks is essential for assessing the forest carbon dynamics. The measurement of carbon stocks can be achieved through an allometric equation, which offers a cost-efficient solution for estimating tree biomass and carbon stocks by measuring only specific tree features, including diameter and height. Many allometric equations have been developed for estimating the forest biomass in tropical región. However, only few studies were found focusing on dipterocarp species, and most of them applying allometric equations for aboveground biomass only. This study sought to refine the accuracy of allometric equations related to Dipterocarp Forest by creating new equations for above-ground, root, and total biomass.
METHODS: The study was conducted in tropical natural and planted forests in Indonesia (Sumatra, Java, and Kalimantan) and Peninsular Malaysia (Johor, Perak, and Pahang), with a total of eight plots at different provinces. Using destructive analysis, all tree samples were collected and divided into groups consisting of living branches and twigs, dead branches and twigs, leaves and roots. A series of general equations for an allometric model has been formulated to assess tree volume and biomass. Then, the allometric equations were validated using validation models.
FINDINGS: Generally, there are a positive relationship between tree diameter and height, tree volume and biomass. he study achieved the successful creation of various equations that represent above-ground, root, and total biomass, based on tree diameter alone and in conjunction with both tree diameter and height. Also, the validation of models against actual data showed that models for above-ground, root-, and total- biomass were not significantly different (probability value > 5 percent). Depending on the forest type, planted forests demonstrate more uniform relationships among tree diameter, height, and biomass components, which suggests the presence of controlled growing conditions. In contrast, natural forests display a higher degree of variability, particularly among larger trees, which mirrors the diversity found in natural ecosystems.
CONCLUSION: Allometric model for estimating biomass in dipterocarp forests was developed and validated using diameter and a combination of diameter and height as predictor variables. The models demonstrated a high coefficient of determination (> 90 percent), indicating strong predictive power for above-ground, root- and total biomass. Based on statistical significance and practical use, Model 1 for above-ground biomass, Model 7 for root biomass, and Model 8 for total biomass were recognized as the most suitable models.

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INTRODUCTION

The dipterocarp forests, distributed across tropical and subtropical regions of Asia, are unique ecosystems that play a critical role in both conservation and production forests. Dominating the lowland landscapes of Indonesia and Malaysia, these forests play a critical role in providing habitats for a wide range of species. Additionally, they are important suppliers of timber and non-timber products, including medicinal plants and resins from dipterocarp species (Huy *et al*., 2019). The conservation and sustainable management of these forests are crucial for climate change mitigation and economic reasons. With the growing global focus on climate change mitigation, it is vital to thoroughly comprehend the dynamics of carbon (C) stocks in forest ecosystems (Debie and Abro, 2025; Siregar *et al.,* 2025). They have important role in regulating the C cycle and global climate mitigation, as forests are significant C sinks and store C dioxide from the atmosphere in biomass and soil (Pant *et al*., 2023). Reliable quantification and forecasting of biomass and carbon in forest ecosystems are necessary for assessing their C sequestration potential (Tian *et al*., 2023; Larekeng *et al.,* 2024). Destructive and non-destructive methods are often used to estimate biomass (Schettini *et al*., 2023). Although destructive techniques offer improved accuracy, they are often time-consuming and costly, involving the collection, oven-drying, and weighing plants (Suárez-Fernández *et al*., 2025). Non-destructive methods are based on allometric equations that related to forest inventory data, such as height (H) and diameter at breast height (D), to tree volume and biomass (Brede *et al*., 2022; Sumarga *et al.,* 2024). Nevertheless, these allometric equations necessitate extensive temporal data for each species and are complicated to scale. In addition, most recent research on forest biomass in the tropics has been conducted using remote sensing technology, which also requires appropriate allometric equations for validating through field measurements (Avitabile *et al*., 2016). To enhance forest management, particularly in relation to carbon sequestration and climate change mitigation, it is crucial to have reliable allometric equations that simplify the estimation of tree biomass of the forest. By having a more accurate and comprehensive biomass estimation model for dipterocarp forests, policy makers and conservation practitioners can optimize forest management strategies to increase C sequestration potential and reduce greenhouse gas emissions. Several field studies have been undertaken to formulate allometric equations that estimate forest biomass in tropical environments to date (Ketterings *et al*., 2001; Basuki *et al*., 2009; Chave *et al*., 2014; Manuri *et al*., 2014; Manuri *et al*., 2016). However, among those existing studies, only two have specifically focused on dipterocarp species, both of which dedicated to develop allometric equation for aboveground biomass (Basuki *et al*., 2009; Manuri *et al*., 2016). Furthermore, both studies conducted field sampling only in natural forest. Consequently, further field studies are required to improve the precision of allometric equations for Dipterocarp forests in tropical regions, utilizing diverse field sampling methods. Moreover, the process of developing an allometric equation for root biomass generally involves a higher level of effort and resource allocation. This study aimed to develope allometric equations of tropical forest biomass including above-ground biomass (AGB), root biomass (RB), and total biomass (TB), specifically focus on dipterocarp forests in tropical countries. To improve the accuracy of these equations, a comprehensive sampling strategy was adopted, both in natural and plantation forests with a wide range of tree age, D, and structure variation. In addition, a significant and diverse array of samples was obtained from multiple islands and countries. The study was conducted in tropical natural and production forests in Sumatra, Java, and Kalimantan as well as Johor, Perak, and Pahang of Indonesia during 2019 to 2022 (Fig. 1 and Table 1).

MATERIALS AND METHODS

Study site

The sites for this study are based in Malaysia and Indonesia, featuring both natural forest ecosystem and dipterocarp plantation forest. The topography ranges from flat to undulating as 5-25 percent (%) slope, with elevation varying between 200 - 600 meters (m) above sea level (asl). In total, eight measurement plots were established, consisting of four plots in natural forest and four in plantation forest (Fig. 1 and Table 1). This natural forest falls under the classification of lowland tropical forest, noted for its diverse mix of dipterocarp species along with other types of trees. These sites illustrate a typical

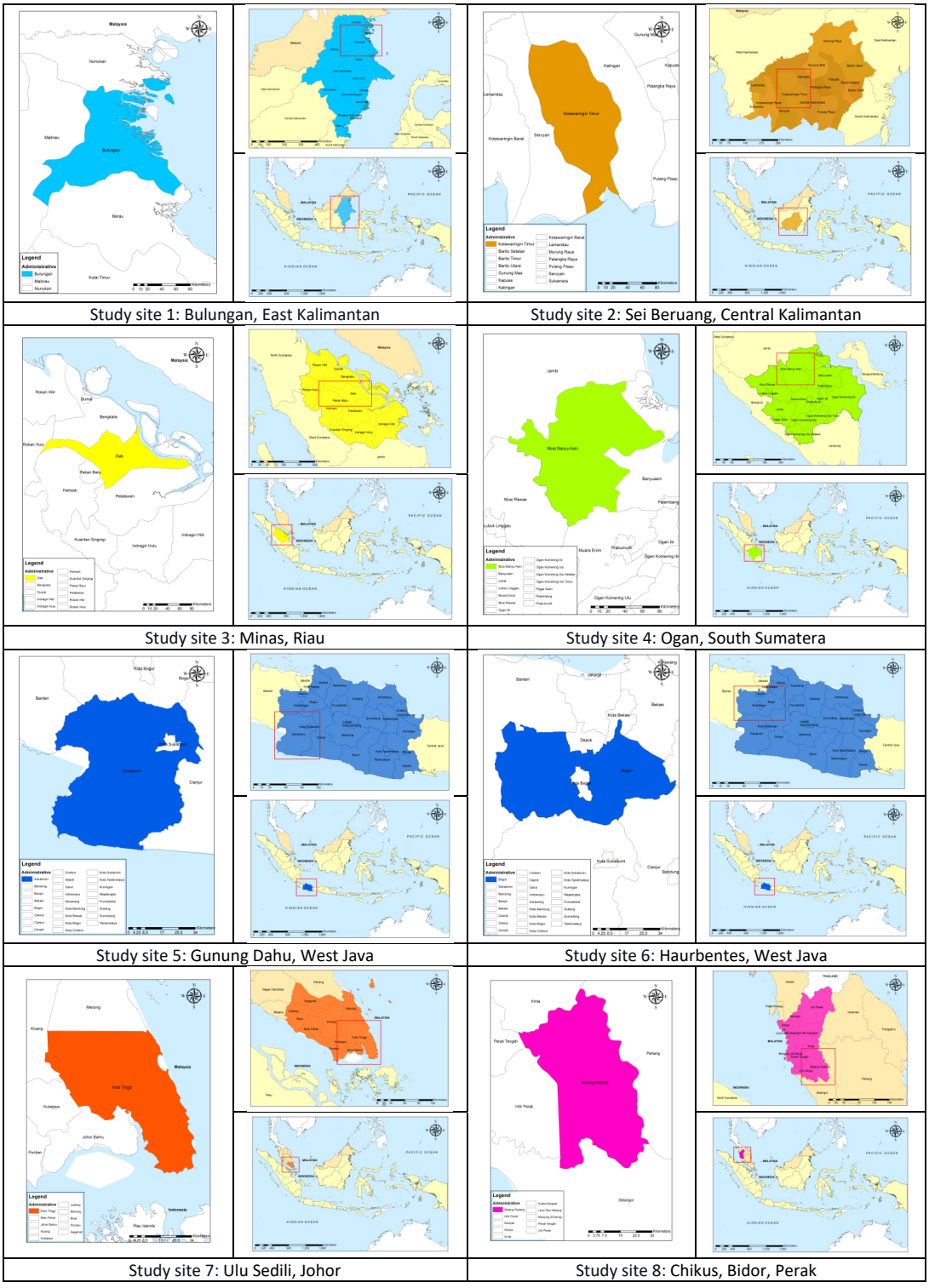

Fig. 1: Geographic location of the study area in in tropical natural production forests in Sumatra, Java, and Kalimantan and Johor, Perak, and Pahang of Indonesia

Table 1: Geographical position of the study plots

No.	Forest type	Site	Geographical coordinates	
Natural forest				
1	Primary forest	Bulungan, East Kalimantan	Latitude longitude altitude	02°56'093" - 02°58'057" North 116°32'557" - 116°35'101" East 200-600 m. asl
2	35 years - logged over area	Sei Beruang, Central Kalimantan	Latitude longitude altitude	00°52'30" - 01°22'30" South 111°30'00" - 112°07'30" East 111- 600 m. asl
3	15 years - logged over area	Minas, Riau	Latitude longitude altitude	00°49'438" – 00°50'138" North 101°28'340" – 101°28'499" East 8 – 100 m. asl
4	10 years - logged over area	Ogan, South Sumatera	Latitude Longitude Altitude	02°14'212" – 02°14'989" South 103°17'182" – 103°17'879" East 54 – 96 m.asl
Planted forest				
1	12 years - Spacing trial	Gunung Dahu, West Java	Latitude longitude altitude	06°36'535" – 06°37'766" South 106°33'844" – 106°35'712" East 694 – 917 m. asl
2	16 years – Ex-situ conservation	Haurbentes, West Java	Latitude longitude altitude	06°32 – 06°33 South 106°20 – 106°30 East 220 – 280 m. asl
3	6.5 years - Provenance trial	Ulu sedili, Johor	Latitude longitude altitude	01°44 – 01°95 North 103°53 – 103°88 East 30 – 60 m. asl
4	17 years - Restoration trial	Chikus, Bidor, Perak	Latitude Longitude Altitude	04°05'338" – 04°05'559" North 101°11'328" – 101°11'462" East 30 – 60 m. asl

sample of the natural forest landscapes that still exist in Southeast Asia. Vegetation analysis indicates that dipterocarp dominate the study area, with tree H up to 35 - 60 m. Additionally, dipterocarps are the predominant species in the stand composition, with individuals having a minimum D of 10 centimeters (cm). The vastness of the site, which covered the Island and several countries, necessitated greater effort and resources for data collection. Also, the times of the study were quite long up to about 4 years to compile the samples. Despite the fact that the sites are located in different countries, the data collection process does not present any major challenges.

Each sample plot measures 20 × 20 meters and has been strategically located to reflect the logging activities performed by the concession permit holder, which supports the collection of destructive sampling data. Data collected from each plot included tree species identification, D and H. Sample selection criteria focused on dipterocarp species with a minimum D of >10 cm. A total of 81 trees were sampled in natural forests, compared to 38 in plantation forests. In the natural forests, tree D's diameter varied from 10 to 75 cm, with the majority of specimens falling within the 20 to 25 cm category. Twenty dipterocarp species were identified, with *Shorea parvifolia* dyer being the most dominant, exhibiting a broad size distribution from <5 cm to 75 cm in D. In plantation forests, tree D ranged from 10 to 25 cm, with the majority in the 10–15 cm class. The dominant species in plantation forests was *Shorea leprosula Miq.* The collection of data for dipterocarp species was conducted without differentiating between the various species within this group. This study was designed to develop an allometric model specifically for dipterocarp species, considering the species diversity within the research plots and the relatively limited number of sampled individuals.

Destructive sampling

Tree samples obtained from natural forests were chosen based on the normality of tree structure during logging companies' operational felling activities. In contrast, samples from plantation forests were chosen based on D distribution. Destructive analysis samples were obtained from all eight plots (Table 2).

Table 2: Species and quantity of harvested samples that were collected from study plots. Superscript P and R mean samples from planted forest and species with roots unearthing, respectively

Group	Species	Quantity	Group	Species	Quantity
Red meranti	*Shorea (S) acuminate* dyer [R]	6	Red Meranti	*S. scaberiana* [R]	1
	S. assamica	1		*S. stenoptera* [R]	2
	S. falax [R]	1		*S. teysmanniana* Dyer	1
	S. glauca King	1		*S. virescens* [R]	1
	S. johorensis [R]	3		*S. xantophylla* [R]	1
	S. laevis [R]	2		*S. bracteolate* dyer [R]	7
	S. leprosula Miq. [R]	41 (38 [P])		*S. polyandra*	1
	S. ovalis Bl.	2	Kapur	*Dryobalanops fusca* V.Sl	3
	S. palembanica Miq [R]	3		*D. lanceolata* burck	1
	S. parvifolia dyer [R]	20	Keruing	*Dipterocarpus appendiculatus* Scheff [R]	5
	S. patoensis [R]	2	Majau	*Shorea compressa* burck	4
	S. pinanga [R]	1		*S. seminis* V.Sl	2
	S. platycarpa [R]	1	Yellow Meranti	*S. gibbosa* brandis	1
	S. platyclados V.Sl	1		*S. faguetiana* dyer	2
	S. polyandra [R]	1	White Meranti	*S. retinodes* V.Sl	2

Instead of cutting down tree D, the sample trees were gathered using a destructive approach that employed digging tools and heavy machinery. Trees with D less than 10 cm were directly pulled out including the root system using digging tools such as hoe, crowbar and hand tracker. The collection of trees exceeding 10 cm in diameter was facilitated by heavy machinery, such as an excavator. Initially, the process involved manually excavating to weaken the root systems, which was then complemented by spraying water using firefighting equipment. Then, followed by utilizing the above-ground weight as a driving force for unearthing the root system. All tree samples then cut and measured for H, D and weight in the field every 2 m. at subsequences of 0-0.3 m, 0.3-1.3 m, 1.3-3.3 m, and so on. Those samples then were categorized into living branches and twigs, dead branches and twigs, leaves and roots. Furthermore, root samples were collected whenever it was practical. All samples were then taken to the laboratory for the purpose of measuring their oven-dry weight. The sample trees with D more than 30 cm in the natural forest were measured with special procedures after felling. The procedures included measuring the stem D at the larger and smaller ends of the stump (the lower section of the stem left in the field after harvesting) and at the larger and smaller ends of substantial branches exceeding 20 cm in D. Moreover, measurements were obtained for the stems classified as commercial and non-commercial, the latter being segments deemed unsuitable for commercial use because of their defects). The tree volume was then calculated using Smalian's formula. Other components, such as small branches, twigs, and foliage, were weighed directly in the field using platform balance. A selection of sub-samples, each weighing 200 grams (fresh weight), was taken from every component and measured using a spring balance. Block-shaped sub-samples (2 cm x 2 cm x 5 cm) of wood from the stump, commercial stem, non-commercial stem, and substantial branches were obtained for biomass estimation, considering their specific wood density. All samples were systematically placed into coded paper bags and subsequently delivered to the laboratory for oven-drying. The biomass samples then were dried at 85 degrees Celsius (°C) until reach consistent weight, using a drying oven (Memmert, Germany). The specific drying duration was: i) 48 hours (h) for leaves and wood biomass less than 10 cm in D, and ii) 96 h for wood biomass over 10 cm in D (Heriansyah *et al.*, 2007; Miyakuni *et al.*, 2004; Miyakuni *et al.*, 2005). Once the dry weight was measured, the total dry weights were derived by taking the initial fresh weight of the samples and multiplying it by the dry-to-fresh weight ratio of each respective sample. The development of this model does not take into account variations in growing conditions such as rainfall, soil type, and

Table 3: Equation for general allometric models

ID	Equation	Model Type
1	$AGB = aD^b$	Exponential
2	$AGB = a(D^2H)^b$	This study
3	$AGB = \frac{aD}{(1+bD)}$	Michaelis-Menten
4	$AGB = \frac{a(D^2H)}{(1+b(D^2H))}$	This study
5	$AGB = exp\ (a + b * lnD - c * (lnD)^2)$	(Brown, 1997)
6	$AGB = exp\ (a + b * ln(D^2H) - c * (ln(D))^2)$	This study
7	$AGB = exp\ (a + b * lnD)$	(Basuki *et al*., 2009)
8	$AGB = exp\ (a + b * ln\ (D^2H))$	(Romero *et al*., 2022)

temperature. The current study seeks to formulate a comprehensive allometric equation for dipterocarps, deliberately omitting specific environmental factors from consideration. This highlights a limitation of the model. Additionally, the model faces the challenge of differentiating components of the sample tree after it has been cut down. The high density of the stand causes the sample tree to be cut down and hit other trees around it. Then all parts of the tree are weighed. It is possible that some parts that are not from the sample tree are also weighed. A further complication is that while extracting and collecting roots from sample trees, it is often the case that not every root is gathered. This leads to uncertainty regarding whether the roots weighed are exclusively from the sample tree, a situation exacerbated by the dense stand. To address the potential sources of error in the destructive sampling method used to collect biomass data, the selection of sample trees considers the normality of the trees, including the ratio of D to H and the proportion of the crown.

Formulating and model fitting of allometric equation

To estimate tree volume and AGB, a set of general equations for allometric model was developed (Table 3). An exponential model was specifically utilized, incorporating D either independently or alongside H as independent variables to evaluate tree volume and biomass (Huang *et al*., 2021). The study assessed the efficacy of linear and non-linear models in log-log space. The linear model is based solely on D as the independent variable, implying a linear D-biomass relationship in log-log space. Concurrently, non-linear models involved employing polynomials in D and incorporated various combinations of both D and H as independent variables.

The assessment of model fit for allometric equations adhered to specific criteria, including the significance of model coefficient at α of 5%, low standard error, high coefficient of determination (R^2), high adjusted coefficient of determination (R^2adj) and a low root mean square error (RMSE) (Chicco *et al*., 2021).

Validation of the allometric equations

A validation analysis was conducted on the dataset comprising 119 sample trees to determine the general applicability of the derived equation. The analysis was conducted using a random dataset that did not involve replacement, and it was divided into two separate subsets. The larger dataset (67%) was utilized for model construction, involving the development of model equations, while the smaller subset (33%) served for model validation. For the construction process, the 67% subset was employed to ascertain the parameters of the equation linking biomass to D, with or without H considerations. Subsequently, the biomass values for the remaining 33% trees were validated based on this equation and compared against the measured biomass. The process involved recording the intercept, slope, R^2, and residual standard error that characterize the relationship between the developed model

Table 4: Distribution of D based on forest and tree type

Forest type	Species	Diameter (cm)																
		<5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65	65-70	70-75	>70	Grand total
Natural	Kapur					3		1										4
	Keruing	1					1			1	1			1				5
	Majau					2	1		1					1			1	6
	Red meranti	16	11	5	4	9		1	2	1	1	1	1	3	2		1	58
	White meranti							1					1					2
	Yellow meranti					1				1						1		3
Total		17	11	5	4	15	2	3	3	3	2	1	2	5	2	1	2	78
Plantation	Red meranti	3	17	11	3	1	4					1	1					41
Total		3	17	11	3	1	4	0	0	0	0	1	1	0	0	0	0	41
Grand total		20	28	16	7	16	6	3	3	3	2	2	3	5	2	1	2	119

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and its validation. To ensure the accuracy of the model, the simulation model was compared with model validation using t-test with an α of 5% (95% confidence intervals). The model was deemed valid if it was determined to be statistically equivalent to the model validation.

RESULTS AND DISCUSSION

Available dataset

This study successfully collected 119 individuals representing 81 trees of Dipterocarp species in natural forest and 38 trees of *Shorea leprosula* in plantation forest (Table 4). The D and H of trees in natural forests ranged from 1.2 – 114.6 cm and 1.9 - 59.1 m, respectively. In the plantation forest, the D and H of the trees varied between 3.7 cm and 28.5 cm, and from 2.9 m to 23.1 m, respectively. Observations of the D distribution indicate that natural forests have a more extensive range of D compared to plantation forests, which is reflected in the elevated D values associated with natural forests. When compared to plantation forests, which are typically well-managed and often consist of a single species, natural forests display a more complex and uneven distribution of tree diameters, along with a greater diversity in tree sizes. Natural forests tend to have a more complex and diverse structure due to the natural processes of natural selection, interactions between species, and ecological succession that occur over a long period of time. The formation of natural forests occurs over time as a result of competition among and within species, which creates variations in wood density and a broad spectrum of tree sizes. Conversely, plantation forests typically exhibit a more consistent structure due to the intentional management practices employed, which often involve the cultivation of genetically uniform species. Compared to planted forests, natural forests tend to have higher specific gravity, leading to higher biomass content. Similarly, with tree D size, it is difficult to estimate the age of trees in natural forests. The longer rotation times of natural forests result in the cultivation of larger trees, which in turn increases the range of the model that is currently being developed.

Proportion of biomass

The proportion of stem biomass to AGB is higher than branches and foliage biomass (Fig. 2). The proportion of stem biomass ranges from 32 to 70%, with an average of 51.7%. The range becomes narrower when considering the first quartile (Q1) and third quartile (Q3), which varies between 46% to 58%. Branch biomass constitutes between 4% and 30% of the total AGB, averaging approximately 17.4%. The proportion of foliage varies from 2 to 26%, with an average of 12%. The proportion of root varies from 10.2 to 32.1%, with an average of 18.4%.

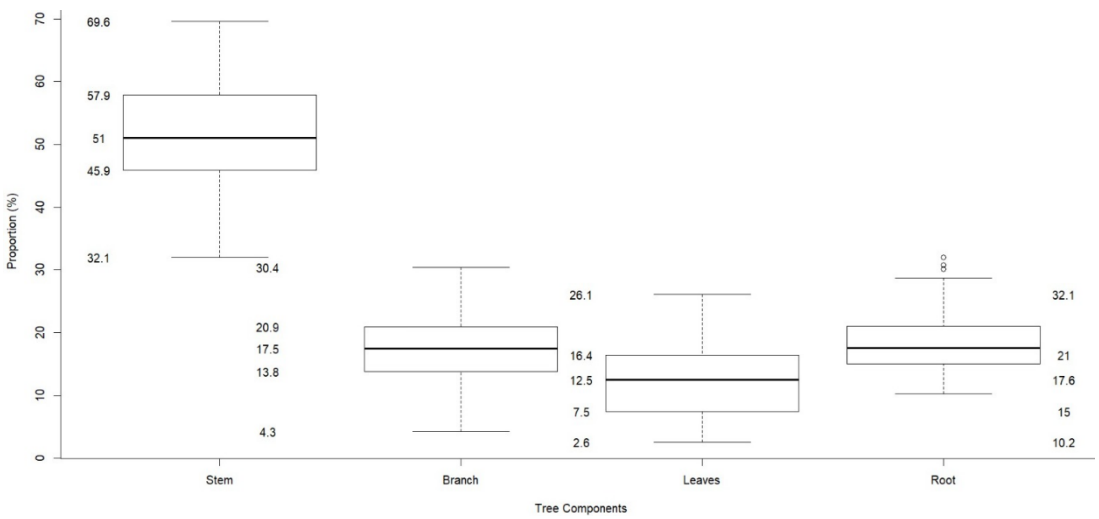

Fig. 2: Boxplot of the proportion of tree component biomass: stem, branches, leaves, and root to TB (%)

Biomass estimation variables

Results from the data distribution concerning biomass variables revealed a positive association between D and H, tree volume and biomass (Fig. 3). D to H and biomass relationship tend to be a relatively stable for planted and natural forests of D less than 20 cm as an effect of similar growing space. In natural forests with a D greater than 20 cm, the results demonstrated a relatively scattered pattern, influenced by the varying availability of growing space and competition among the trees.

Allometric model for biomass

Several equations using all data from natural and plantation forest were constructed following the scenarios for ABG, RB, and TB biomass using parameter D alone and a combination of D and H (Table 5).

Based on the criterion of R^2 and R^2adj, almost all models have high coefficient determination (>90%) except models 2 and 3. In terms of significance, where the coefficient is below 5%, models 1, 4, and 5 were recognized as the top-performing models, with model 1 being the most applicable. Unlike the AGB equation, almost all models for RB have moderate coefficient determination. However, when considering significance (coefficient less than 5%), model 7 emerged as the best-fitting model (Table 6).

For TB, based on the criteria of R^2 and R^2adj, almost all models have high coefficient determination (>94%), except models 3 and 4. Nevertheless, when evaluating significance at a coefficient of less than 5%, model 8 proved to be the optimal fitting model (Table 7).

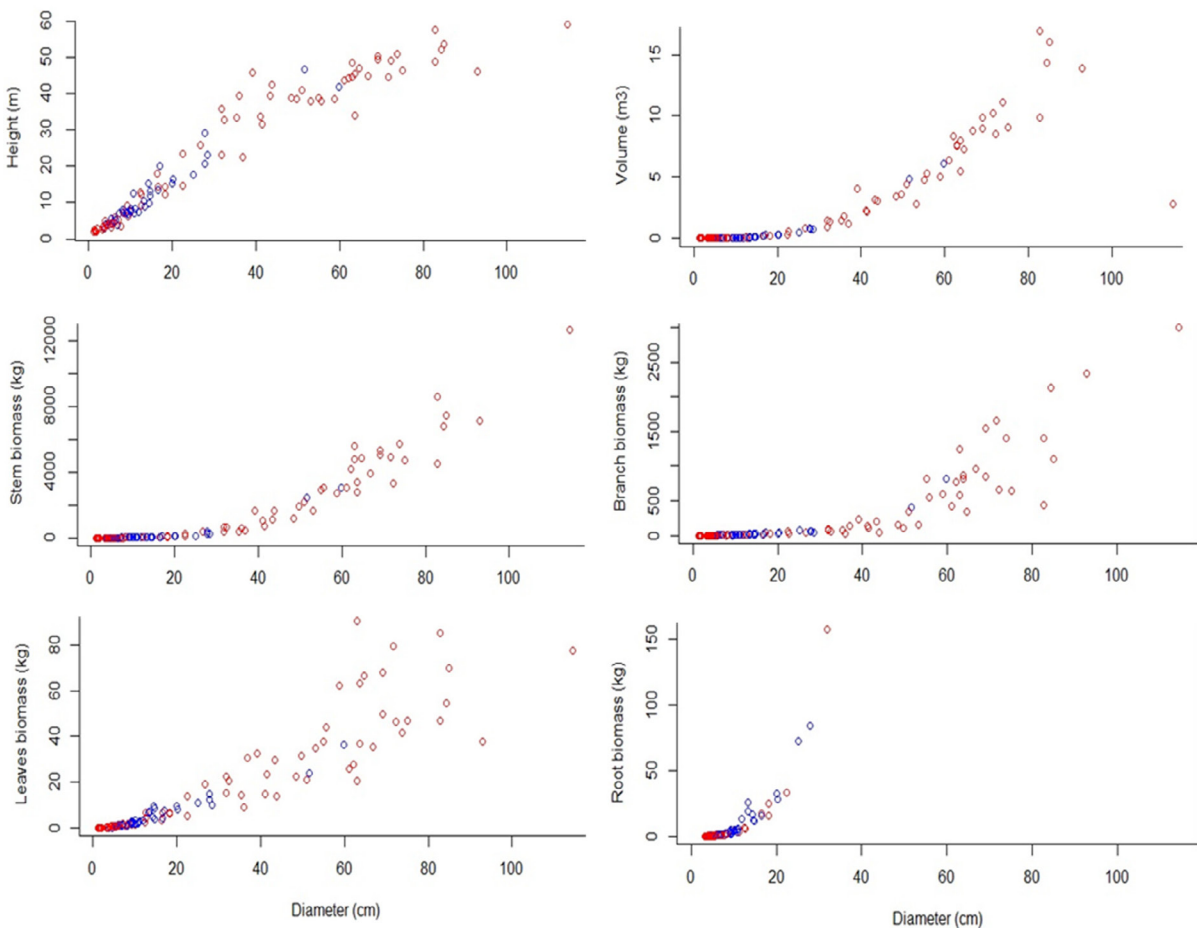

Fig. 3: Relationship between D and H, volume, stem, branch, leaves, and root-biomass. Red and blue colors represent natural and planted forests, respectively.

Table 5. Characteristics of allometric models for ABG

Model	R^2	R^2adj	RMSE	Coefficient		
				a	b	c
1	0.949	0.949	67.11	0.4244**	2.222***	
2	0.959	0.959	42.85	0.084*	0.8968***	
3	0.144	0.133	1063.09	5.4028*	0.8968***	
4	0.885	0.884	388.4	0.5614 ***	-7.9e-07 ***	
5	0.953	0.953	8.5	-9.867*	6.4095**	-0.4843
6	0.961	0.960	24.18	-4.956**	1.245***	-0.1
7	0.950	0.949	67.11	-0.857*	2.222***	
8	0.960	0.959	42.85	-2.474***	0.897***	

*Significant at 10% significant level, **Significant at 5% significant level, ***Significant at 1% significant level

Table 6: Characteristics of allometric models for RB

Model	R^2	R^2 adj	RMSE	Coefficient		
				a	b	c
1	0.867	0.867	0.314	0.028*	2.309***	
2	0.831	0.828	0.173	0.028	0.787***	
3	0.81	0.807	0.957	0.463***	-0.032***	
4	0.786	0.781	1.03	6.34e-01***	-8.23e-05***	
5	0.89	0.89	0.09	-14.647**	10.472**	-1.492*
6	0.86	0.85	19.73	-1.597	0.262	0.295**
7	0.87	0.87	0.314	-3.575***	2.309***	
8	0.83	0.83	0.831	-3.579***	0.787***	

*Significant at 10% significant level, **Significant at 5% significant level, ***Significant at 1% significant level

Table 7: Allometric model for TB

Model	R^2	R^2 adj	RMSE	Coefficient		
				a	b	c
1	0.927	0.925	1.4	0.094*	2.484***	
2	0.953	0.951	0.1	0.05**	0.925***	
3	0.86	0.857	5.326	2.391***	-0.033***	
4	0.19	0.17	25.11	6.34e-01***	-8.23e-05***	
5	0.96	0.96	1.02	-15.28***	11.85***	-1.69**
6	0.97	0.96	0.363	-2.46***	0.79***	0.07
7	0.94	0.94	1.4	-2.367***	2.484***	
8	0.96	0.96	0.1	-3.00***	0.925***	

*Significant at 10% significant level, **Significant at 5% significant level, ***Significant at 1% significant level

The allometric equation for tree volume and biomass was validated using the biometric data (Fig. 4, Table 8). The validation of models against actual data revealed no significant differences among the models for AGB, RB, and TB were not significantly different (probability value (p-value)) > 5%) (Table 8). The p-value of RB were quite low compared to AGB and TB. However, RB estimation in this study only need a data of D, same as AGB. While, for TB, the model need a combination data of D and H.

Comparative biomass predictions

Comparative analysis was conducted by evaluating the efficacy of the present equation against literature-based models. The plot-level biomass predicted by the optimum predictive equation derived in this study, employing the composite variable D while excluding the effect of forest type, were compared with those from various functions found in the literatures both in dipterocarp forest or non dipterocarp or mixed forest (Table 9). The results of the analysis, depicted in Fig. 5, showcase the comparisons made for equations based entirely on the log-log linear function of D for (Basuki *et al*., 2009; Brown, 1997; Chave *et al*., 2005), respectively.

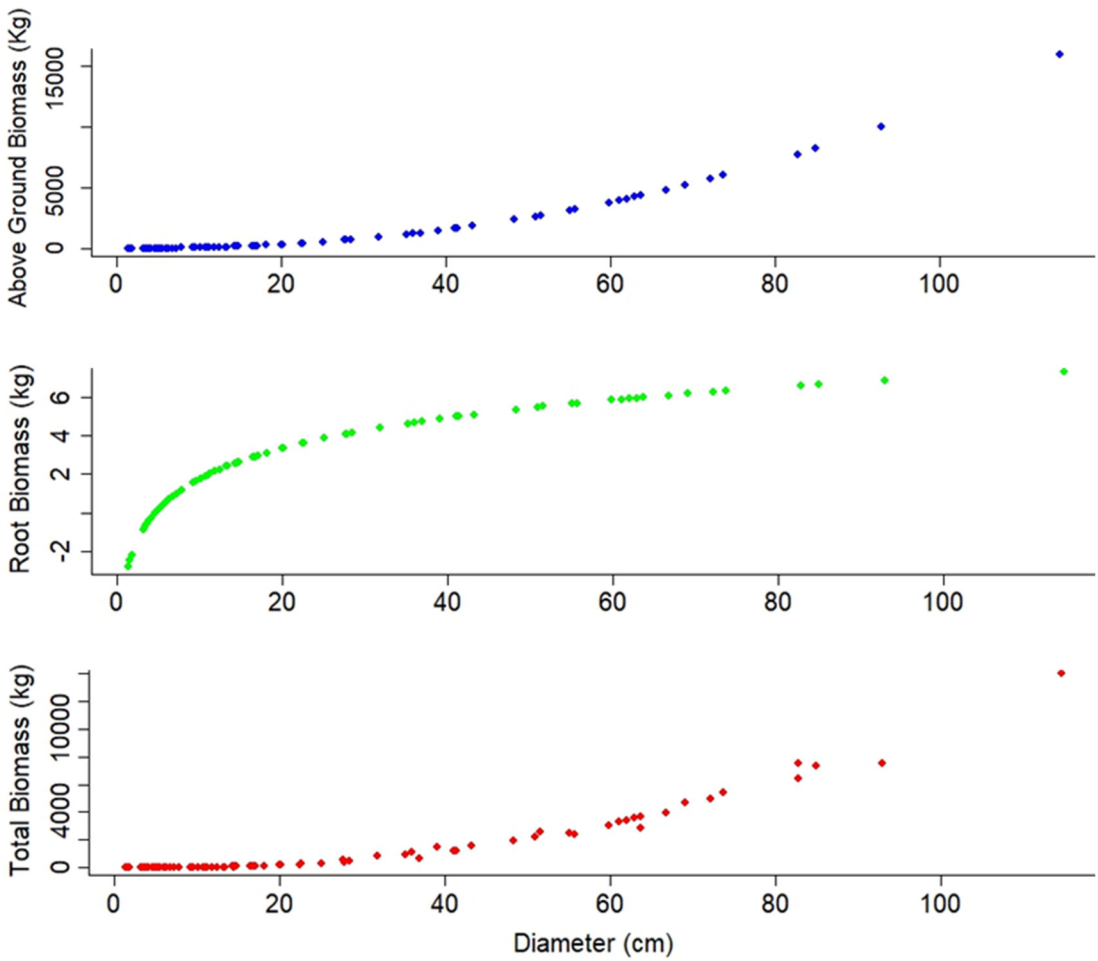

Fig. 4: Ratio observed value with model allometric

Table 8: Validation test for AGB, RB, and TB

Biomass	Equation	t-test	p-value
Above ground	$\mathrm{AGB} = 0.4244(\mathrm{D})^{2.222}$	0.017	0.986
Root	$\mathrm{RB} = -3.575 + 2.309(\ln \mathrm{D})$	0.60	0.55
Total	$\mathrm{TB} = \exp(-3.00 + 0.925 * (\ln \mathrm{D}^2\mathrm{H})$	-0.016	0.987

In dipterocarp forest, the average deviation for individual trees models by Basuki *et al*. (2009) is lower than that of the study model (Fig. 5). In contrast to non-dipterocarp forests, the model examined in this study exhibits a greater average deviation (Ketterings *et al.,* 2001). The predicted values in the study were underestimated if the equation from Ketterings *et al.* (2001) were applied in the data of this study. However, the model developed by Manuri *et al*. (2014) and Brown (1997) in mixed forest has similar estimates for AGB at a deviation between 1 to 19% (average 10%) for D 35 to 115 cm, and a deviation between 1 to 20% (average 4%) for D 15 to 115 cm, respectively. In addition, the paired t-test presented in Table 8 shows that for one-tailed at α = 0.05, the mean of our model is significantly similar at p-value 0.81 and 0.88 for the model of Manuri *et al*. (2014) and Brown (1997), respectively. Brown (1997) developed an equation

Table 9: The comparison of equations based on the log linear function of tree D

No.	Equation	t-test	p-value	Sources
1.	$AGB = 0.108 * (D)^{2.562}$	0.244	0.810	Manuri *et al.*, 2014
2.	$AGB = 0.318 * (D)^{2.196}$	1.700	0.080	Basuki *et al.*, 2009
3.	$AGB = 0.066 * (D)^{2.59}$	1.320	0.188	Ketterings *et al.*, 2001
4.	$AGB = 42.69 - 12.8 * D + 1.242 * D^2$	0.150	0.880	Brown, 1997

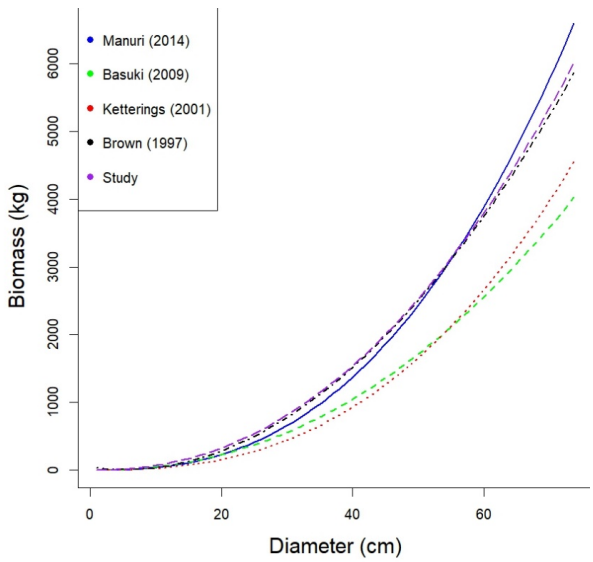

Fig. 5: Comparison of plot-level biomass using alternative equations from literature.

that almost precisely estimated the plot ABG relative to the equation developed here in all four cases. Comparative analysis with literature-based models (Basuki *et al.*, 2009; Brown, 1997) showed that the study's models provided comparable or improved estimates for AGB, particularly for larger D classes. While the model from this study is comparable to findings from some non-dipterocarp forest studies, using a species grouping model significantly improves the precision of the estimation (Manuri *et al.*, 2014).

Biomass Conversion and Expansion Factor (BCEF)

This study's BCEF is associated with estimating TB from AGB. If AGB is estimated from D, the resulting estimation, when multiplied by the BCEF, provides the TB (Schepaschenko *et al.*, 2018). The definition of BCEF depends on what is being estimated; at times, BCEF is utilized to calculate TB in hectares (ha), as demonstrated by Marziliano *et al.* (2017) which influences its applicability. Marziliano *et al.* (2017) emphasize that BCEF plays a crucial role in estimating the TB of stands using allometric equations. In cases where the equation is unknown, the BCEF used is based on stand age. BCEF is also expressed as the proportion of carbon dioxide (CO_2) in tree volume, denoted in ton carbon dioxide per cubic meter (tCO_2/m^3) (Petersson *et al.*, 2012).

The value of BCEF is a crucial conversion factor for estimating TB from D parameters (Fig. 6). D is employed to estimate AGB, and the estimation of TB is derived by multiplying AGB and BCEF. Fig. 6 shows BCEF distribution at different D, with an average of 1.22 at a standard deviation of 8% (Table 10). As indicated in Table 10, the BCEF is 1.22 for the dipterocarp species, signifying that the TB is approximately 1.22 times the AGB. This BCEF value is practical within D range of 3.2 to 31.8 cm. The BCEF value of 1.22 indicates that TB is approximately 1.22 times the AGB, providing a practical conversion factor for dipterocarp species within a D range of 3.2 to 31.8 cm.

Predictive variables of allometric equations model

Results from the validation of the models against

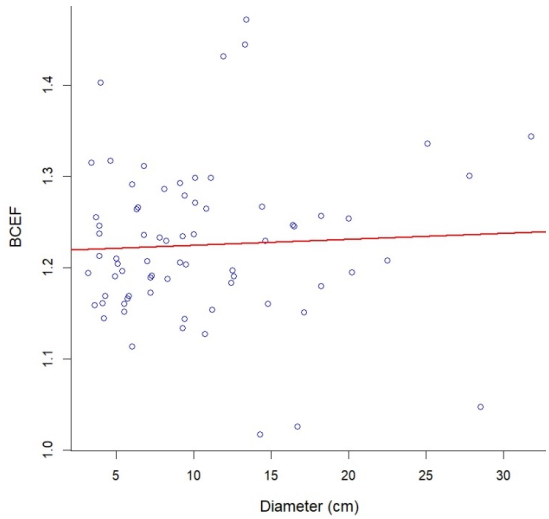

Fig. 6: BCEF value distribution at several D of trees

Table 10: BCEF for D ranges of dipterocarp species in tropics

D (cm)		BCEF			
Min	Max	Min	Max	Average	Deviation
3.2	31.8	1.02	1.47	1.22	0.08

actual data demonstrate a positive association with D (Fig. 4). Also, the models for AGB, RB, and TB were not significantly different from actual data, supporting their use for biomass estimation in dipterocarp species. This positive correlation implies that the models formulated in the research can effectively estimate the biomass of dipterocarp species within Indonesia's tropical dipterocarp forests (Basuki *et al*., 2009; Huy *et al*., 2016; Manuri *et al*., 2014; Manuri *et al*., 2016). In the context of dipterocarp species, the allometric equation utilizing D or a combination of D and H as predictor variables displayed consistent stability across the thirty dipterocarp species (Basuki *et al*., 2009; Chave *et al*., 2005; Hashimoto *et al*., 2004; Huy *et al*., 2016; Huy *et al*., 2019). The data reveals a stark contrast between the natural and plantation forests in terms of species diversity. The natural forest exhibits a rich composition of Dipterocarp species, including Kapur, Keruing, Majau, Red meranti, White meranti, and Yellow meranti. In contrast, the plantation forest consists exclusively of Red meranti (*S. leprosula*). This difference aligns with (Basuki *et al*., 2009; Huy *et al*., 2016; Manuri *et al*., 2014; Manuri *et al*., 2016) typical patterns observed in tropical forest ecosystems, where natural forests generally support higher biodiversity compared to monoculture plantations. In the natural forest, the D distribution displayed a reverse J-shaped curve, a hallmark of mixed-species forests characterized by uneven age distribution. About 66.7% of trees fall within smaller D classes (<25 cm). Large trees (>50 cm D) constitute only 16.7% of the total, indicating the presence of old-growth elements. Meanwhile, D distribution at planted forest showed more uniform D distribution, concentrated in 5-15 cm range (82.9% of trees). Maximum D reaches only 25-30 cm, suggesting a relatively young, even-aged stand. Contrast in D distribution reflects the fundamental differences between natural forest dynamics and managed plantation growth (Malik *et al.,* 2024). The robust proliferation of Dipterocarp species in their native forests might play a role in shaping allometric equations for biomass assessment. However, dipterocarp species are highly adaptable to the environment, especially light. The availability of light directly affects tree growth. Therefore, tree size is a key determinant of biomass, which subsequently shapes the dynamic allometric relationship. The allometric equations for planted forests were different with natural forests and

may the influence forest management practices. The consistent growth and lighter specific gravity found in planted forests yield less biomass than equivalent-sized trees in natural forests. In terms of forest management, tree size is a priority in planted forest management, while selective cutting is a primary consideration for natural forest management. Unlike natural forests, plantation forests create a managed setting that encourages a more uniform development of Dipterocarp species. This uniformity is achieved through a combination of ecological and management practices that directly influence the development and biomass accumulation of these trees. Natural forest root biomass is distributed across a wider range of D classes, up to 30-35 cm. A sophisticated subterranean framework that could play a role in improving ecosystem stability (Bardgett and van der Putten, 2014; Poorter *et al*., 2015). Root biomass in plantation forest is concentrated in the 5-15 cm D classes. Reflects a more homogeneous subsurface structure, which is typical of plantations that are even-aged. Estimating root biomass is often a challenge in forest biomass research. Root biomass is difficult to measure directly and requires careful sampling techniques. Moreover, variability in root distribution in the soil and the complexity of root structure can also complicate root biomass estimation. Consequently, additional study and the creation of more sophisticated techniques are essential to tackle the difficulties in precisely estimating root biomass. The study reveals distinct patterns in biomass allocation among different tree components. At stem biomass constitutes the largest proportion of AGB, ranging from 43.6% to 97%, with an average of 71.5%. With an interquartile range spanning from 60.2% to 81.2%, it can be inferred that the majority of trees consistently allocate a considerable amount of their biomass to stems. Branch biomass are representing a smaller but significant portion of AGB, ranging from 2.09% to 40.1%, with an average of 19.5%. The foliage biomass is forms the smallest component of AGB, ranging from 0.38% to 29.1%, with an average of 7.8%. The root biomass area accounts for 14.6% to 21.05% of total biomass, averaging 17.3%. Individual trees may show wider variation (1.7% to 32.1%) as reported by Heryati *et al*. (2011). This biomass allocation pattern aligns with the pipe model theory proposed by Lehnebach *et al.* (2018), which suggests that trees allocate resources to maintain a functional balance between water-conducting tissue (stem) and photosynthetic organs (leaves). The elevated stem biomass ratio demonstrates the trees' focus on structural support and water transport, which are critical for their survival and growth in forest ecosystems. This pattern is consistent with findings from other tropical forests, as reported by Poorter *et al.* (2015), who observed that stem biomass typically accounts for 72-79% of AGB in tropical trees. By integrating stem biomass variation into the model, this study has produced results that are predominantly aligned across different species and ecosystems. With these results, aboveground or total biomass, and sometimes root biomass, can be estimated from stem biomass. Once a tree has been transformed into a log, the volume of waste biomass that remains in the forest can still be assessed. The study demonstrates positive relationships between D, H, tree volume, and biomass components. The relationship between D and H is positively correlated, which is in line with the allometric growth patterns found in trees. The relationship is more consistent in planted forests and for trees with D < 20 cm in natural forests, likely due to similar growing conditions. Greater variability in D-H relationships for trees with D > 20 cm in natural forests, reflecting diverse growing spaces and competition levels. The performance of biomass varies according to forest type. In the case of planted forests, there is a more consistent correlation between D, H, and biomass components, which suggests that these forests are cultivated under controlled. Natural forests exhibit greater variability, especially for larger trees, reflecting the heterogeneity of natural ecosystems. These relationships are consistent with findings from Chave *et al*. (2014) who developed improved allometric models for tropical trees, emphasizing the importance of tree D, H, and wood density in estimating biomass. The fluctuations seen in natural forests, particularly among larger trees, are consistent with the research conducted by Feldpausch *et al*. (2011), which highlighted significant disparities in H-D relationships across diverse tropical forest types and areas. The significant proportion of root biomass (averaging 17.3%) highlights the importance of belowground C storage and soil stabilization. The findings on root biomass align with the global analysis by Cairns *et al*. (1997), who reported that root biomass in upland forests typically ranges from 18% to 30% of aboveground biomass, highlighting the significant contribution of roots to total forest biomass and C

storage. Qi *et al*. (2019), who observed that plants would allocate more biomass to roots to release the stress of water shortage and improve the effectiveness of nutrient and soil moisture. Variations in the biomass ratios of branches and leaves in natural forests may reflect the existence of diverse habitats suitable for canopy-dwelling species. These implications are supported by the work of Thompson *et al.* (2011), who emphasized the importance of forest biodiversity in delivering ecosystem services. This study delivers significant understanding of biomass allocation trends and growth interrelations in natural forests as well as in planted environments like community forest plantation. The findings emphasize the importance of considering forest type and tree size when estimating biomass and C stocks. Moreover, the findings of the study point to the requirement for management practices that are specifically designed to address the unique structural and functional characteristics of both natural and planted forest ecosystems. As suggested by Stephenson *et al*. (2014) the continuous increase in C accumulation with tree size underscores the importance of conserving large trees in natural forests for climate change mitigation strategies. Within the diverse range of ecosystems, the allometric equation formulated in this research acts as a crucial benchmark, reconciling overestimations and underestimations in the data, thereby mitigating possible errors. Therefore, the model will be effective for use in extensive forests with large datasets, but may be less accurate for plants with abnormal growth. Applying the model to planted forests with relatively uniform growth would be better if using a model from planted forests, and vice versa. Nevertheless, for extensive biomass estimation across diverse ecosystems, particularly when time and financial resources are limited, the model from this study will be effective and efficient. In addition, the application of the models to other dipterocarp species in is promising, but needs to consider the variability of environmental conditions that may differ in each region. Some considerations are needed to ensure broader application in different regions include:

1) Model calibration: The created models require modification to reflect the specific attributes of the leading dipterocarp species in various tropical region. Genetic and ecological variability among tree populations in different regions can affect the allometric relationships between the parameters used in the model. 2) Validation: To confirm the reliability of the models, it is essential to test them in different tropical regions, taking into account the distinct environmental conditions present. Validating the models with actual data from different locations can help assess the generalizability of the models. 3) Inclusion of additional parameters: To improve the model's accuracy, it is beneficial to integrate region-specific parameters that consider diverse environmental factors, including soil conditions, climate, and topography. 4) Collaboration and knowledge exchange: Collaboration among researchers from various tropical regions can help broaden the understanding of environmental condition variability and model adjustments. Knowledge exchange among experts can enrich the approaches used to expand the application of the models. By considering these factors, the application of the developed models to dipterocarp species in various tropical regions can be more successful and relevant to estimate tree biomass in different environments. It is anticipated that the allometric model from this research will provide a precise basis for ground truth data, aiding in the future large-scale estimation and monitoring of biomass using remote sensing techniques. Different forest cover typologies provide different image reflections. Thus, by knowing the biomass content of each different forest typology, the biomass contained in the forest could be estimated based on remote sensing. In addition, changes in forest cover based on the results of growth parameter measurements can be linked to the magnitude of C sequestration and climate change mitigation using the model from this study.

CONCLUSION

The study shows a direct field study in 8 different sites across 2 countries with a big forest holder in Southeast Asia, resulting in a wide range of data that is feasible for developing an accurate allometric model and indicating their potential applicability beyond the immediate study regions. Furthermore, samples were sourced from two different forest categories: natural and plantation. This approach ensures a robust sample that improves the model's precision. With a larger number of samples, more diverse species, and different forest types, this study produces an allometric model with broader application and more reliable results compared to other allometric models with more limited data. Findings from the study reveal that the variety of

trees in natural forests is more diverse compared to those in plantation forest. That data reveals that the growth of dipterocarp species in natural forest is more dynamic than that in plantation forest. The samples collected for this study are more than adequate, as they cover a full spectrum of D distribution, ranging from small to large trees, and include a diverse array of tree ages from young to mature, especially in the natural forest setting. Also, the study shows that the composition of dipterocarp species in natural forest is more heterogeneous than that in plantation forest. In simpler terms, the variety of life found in natural forests is considerably richer than that found in plantation forest. This study produces the best-fitting of 3 models of allometric equation with a combination predictor of D and H for estimating the biomass of dipterocarp species in the tropics (model 1, ABG = $0.4244(D)^{2.222}$; model 7, RB = $-3.575 + 2.309\ (\ln D)$; and model 8, TB = $\exp(-3.00 + 0.925 * (\ln D^2 H))$. The models were statistically valid as shown by a high coefficient of determination (R^2 > 90%) and not being significantly different from the validation test's actual data. Those accurate allometric models offer a significant advantage in practical applications to estimate the 3 variables of dipterocarp species biomass, AGB, RB, and TB by only employing the D or a combination of D and H as predictor variables. This study's allometric model for RB holds considerable practical significance, especially since estimating the root biomass of dipterocarp species often necessitates extensive direct measurement efforts in the field. Additionally, if the measurement of tree H is difficult in the field, especially for large trees, the TB could be estimated as the sum of ABG and RB, which requires D measurement only. Thus, increases the simplicity in the field process. In the next step, combining with the C content of trees, the biomass estimation from allometric equations in this study could also improve the accuracy of C stock or sequestration of dipterocarp forest estimation. In general, the study findings provide an important contribution to enhancing the accuracy of biomass and C dynamic estimation of dipterocarp forest, which is essential to support the sustainable forest management in tropical countries. This study's model may face limitations, particularly because it has not yet incorporated variables such as rainfall, soil type, and temperature that could impact its performance. However, with the assumption that the environmental conditions across the tropical countries are usually similar, the model developed in this study is potential to apply beyond the study areas. In addition, the model in this study were developed from samples across different province and country. A further limitation is that the stand's elevated density could result in the integration of elements from surrounding trees into the measurements, thereby potentially biasing the outcomes. The dense forest environment could also complicate the accuracy of root biomass measurements. Collecting roots from sample trees presents challenges in ensuring the complete transport of all origins and verifying that the weighed roots are exclusively from the sample tree. Expanding the range of dipterocarp species in future studies is essential for enhancing the models' generalizability across different forest types and conditions. Also, more studies on the effect of environmental growth conditions such as soil type, climate, and topography are needed to improve the model accuracy and applicability. Furthermore, conducting longitudinal studies to track growth patterns over time would provide insights into biomass dynamics and C sequestration potential. The allometric model tailored for specific sites serves as an essential foundation for developing biomass estimation models based on land cover. In the future, the accurate allometric models that combine with remote sensing data could facilitate large-scale biomass estimation and monitoring faster and more precisely.

AUTHOR CONTRIBUTIONS

I. Heriansyah has contributed in conceptualization, planned the experiment, data collection, data analysis, interpreted and discussed the results, article writing and funding acquisition. L. Abdulah performed in article writing, data analysis and curation, results interpretation, and visualization. J.S. Rahajoe has contributed in article writing, data analysis, editing, results discussion and validation. R. Susanti has contributed in article writing, data analysis, editing, and results discussion. Y. Lisnawati has contributed in article writing, data analysis, editing, and results discussion. Subarudi has contributed in article writing, data analysis, editing, and results discussion. R. Dewi has contributed in article writing, data analysis, editing and validation. Darwo has contributed in article writing, data analysis, editing and validation. Mawazin has contributed in article writing, editing

and validation. Abdurachman has contributed in article writing, editing and validation. Karmilasanti has contributed in article writing and editing. N. Wakhid, the corresponding author has contributed in article writing, editing, validation, results interpretation and discussion. D. Wicaksono, has contributed in article writing, editing and data visualization. R. Effendi has contributed in article writing, editing and validation. A.S Yunianto has contributed in article writing, editing and data visualization. M.A. Qirom has contributed in article writing, editing and data interpretation. N. Mindawati has contributed in article writing, editing and data interpretation.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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The author(s) declare that no AI tools or services were not used or not highly applied during the preparation of this work.

ABBREVIATIONS

%	Percent
^oC	Degree Celsius
AGB	Above-ground biomass
asl	Above sea level
BCEF	Biomass conversion and expansion factor
BGB	Below-ground biomass
C	Carbon
cm	Centimeter
CO_2	Carbon dioxide
D	Diameter at breast height
FOERDIA	Forestry and Environment Research, Development, and Innovation Agency
H	Height
h	Hours
ha	Hectare
Kg	Kilogram

m	Meter
p	Planted forest
p-value	Probability value
Q1	First quartile
Q3	Third quartile
R	Roots unearthing
R^2	Coefficient of determination
R^2adj	Adjusted coefficient of determination
RB	Root biomass
RMSE	Root mean square error
S	Shorea
TB	Total biomass
tCO_2/m^3	Ton carbon dioxide per cubic meter
UPM	Universiti Putra Malaysia
UK	University of Edinburgh

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