Allometric equations for estimating the above-ground biomass in tropical lowland *Dipterocarp* forests

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ABSTRACT

Allometric equations can be used to estimate the biomass and carbon stock of forests. However, 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) ranging from 6 to 200 cm. Destructive sampling was used to collect the samples where diameter at breast height (DBH), commercial bole height (CBH), and wood density were used as predictors for dry weight of total above-ground biomass (TAGB). Model comparison and selection were based on Akaike Information Criterion (AIC), slope coefficient of the regression, average deviation, confidence interval (CI) of the mean, paired *t*-test. Based on these statistical indicators, the most suitable model is ln(TAGB) = $c + \alpha$ln(DBH). This model uses only a single predictor of DBH and produces a range of prediction values closer to the upper and lower limits of the observed mean. Model 1 is reliable for forest managers to estimate above-ground biomass, so the research findings can be extrapolated for managing forests related to carbon balance. Additional explanatory variables such as CBH do not really increase the indicators' goodness of fit for the equation. An alternative model to incorporate wood density must be considered for estimating the above-ground biomass for mixed species. Comparing the presented equations to previously published data shows that these local species-specific and generic equations differ substantially from previously published equations and that site specific equations must be considered to get a better estimation of biomass. Based on the average deviation and the range of CI, the generalized equations are not sufficient to estimate the biomass for a certain type of forests, such as lowland *Dipterocarp* forests. The research findings are new for *Dipterocarp* forests, so they complement the previous research as well as the methodology of the Good Practice Guidance for Land Use and Land Use Change and Forestry (GPG-LULUCF).

1. Introduction

The accurate estimation of biomass in tropical forests is crucial for many applications, from the commercial exploitation of timber to the global carbon cycle. Particularly in the latter context the estimation of the total above-ground biomass (TAGB) with an accuracy sufficient to establish the increments or decrements in carbon stored in the forest over relatively short periods of time (2–10 years) is increasingly important. Under the United Nations Framework Convention on Climate Change (UNFCCC), countries have to report regularly the state of their forest resources and emerging mechanisms, such as Reducing Emissions from Deforestation in Developing Countries (REDD), and they are likely to require temporally and spatially fine-gained assessments of carbon stock (UNFCCC, 2008).

Carbon stock is typically derived from above-ground biomass by assuming that 50% of the biomass is made up by carbon. The most accurate method for the estimation of biomass is through cutting of trees and weighing of their parts. This destructive method is often used to validate others, less invasive and costly methods, such as the estimation of carbon stock using non-destructive in-situ measurements and remote sensing (Clark et al., 2001; Wang et al., 2003). Allometric equations developed on the basis of sparse measurements from destructive sampling are related to more easily collected biophysical properties of trees, such as diameter at breast height (DBH) and commercial bole

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height (CBH). The estimation of carbon over large areas using remote sensing is supported by correlating the reflection of the canopy recorded at the sensor to the carbon measured directly or estimated indirectly on the ground (Chiesi et al., 2005; Gibbs et al., 2007; Myeong et al., 2006; Tan et al., 2007).

In this research, tree allometric equations are developed by establishing the relationship between tree parameters such as DBH, CBH, and wood density with above-ground biomass. Various allometric equations have been developed for tropical rain forests (Araújo et al., 1999; Brown, 1997; Chambers et al., 2001; Chave et al., 2001, 2005; Keller et al., 2001; Nelson et al., 1999). However, there are few allometric equations developed specifically for lowland Dipterocarp forests, despite the fact that this type of forest covers extensive areas in tropical South-East Asia: around 59% of forests in Kalimantan and 53% of forests in Sumatra, Indonesia (Tyrie, 1999), and that they are among the most commercialized hard wood species from South-East Asia. So far, allometric equations for multi-species tropical forests of Indonesia have been published in Brown (1997), Hashimotio et al. (2000), Ketterings et al. (2001) and Yamakura et al. (1986). The applicability of the equations needs to be affirmed before they can be applied to monotypic Dipterocarp forests.

Brown (1997) developed allometric equations for tropical forests using data collected from Kalimantan and other tropical regions. A logistic curve based on tree age was constructed by Hashimotio et al. (2000) in fallow forests of East Kalimantan. The equation of Hashimotio et al. (2000) cannot be applied to Dipterocarp forests as it requires stand age as explanatory variable which is not available, and due to the differences in ecological environments between fallow and natural forests. Ketterings et al. (2001) established an allometric equation in mixed secondary forest in Sumatra, but this forest was not classified as Dipterocarp forest. Yamakura et al. (1986) constructed allometric equations using data collected from Dipterocarp forests from Sebulu, East Kalimantan. They used DBH and tree height to predict stem dry weight. The stem dry weight was used to predict branch dry weight, and stem and branch dry weight was then used to model leaf dry weight. The equations developed by Yamakura et al. (1986) are not practical for most uses since the equation does not directly predict the TAGB.

The lack of allometric equations for Dipterocarp forests is also evident in the Good Practice Guidance for Land Use and Land Use Change and Forestry or GPG-LULUCF (IPCC, 2003; further abbreviated as GPG). In this document, there are only two allometric equations for tropical forests, while in fact there are many differences in the characteristics of tropical forests. The accuracy or uncertainty of models is an important aspect that is mentioned in the GPG and the different instruments of the Kyoto Protocol. To reduce uncertainty, accurate carbon accounting methods are required. The development of new, species-specific allometric equations are necessary to achieve higher levels of accuracy, and we present some new equations here to achieve a better estimation of carbon stock for tropical lowland Dipterocarp forests.

2. Methods

2.1. Study area

The study was executed at two sites in Berau Regency, East Kalimantan, Indonesia. The first site is located in Labanan (1°45′ to 2°10′ North latitude and from 116°55′ to 117°20′ East longitude), Teluk Bayur District. In this location, trees with the diameters (DBH or above buttresses) mostly ranging from 5 to 70 cm were felled. The second site is in the Puji Sempurna Raharja forest concession area, Merancang, around 60 km North-East of Labanan (2°11′ to 2°20′ North latitude and 117°38′ to 118°11′ East longitude), where trees with diameters of 70 up to 200 cm were felled. These study areas are located within the same forest type, namely lowland mixed Dipterocarp. The dominant family in these forests is Dipterocarpaceae. These forests consist of commercial, non-commercial and protected species. The map of the study area is presented in Fig. 1.

Based on the data from 1971 to 1997, the mean annual rainfall in the study area is 2000 mm. The months from June to October are
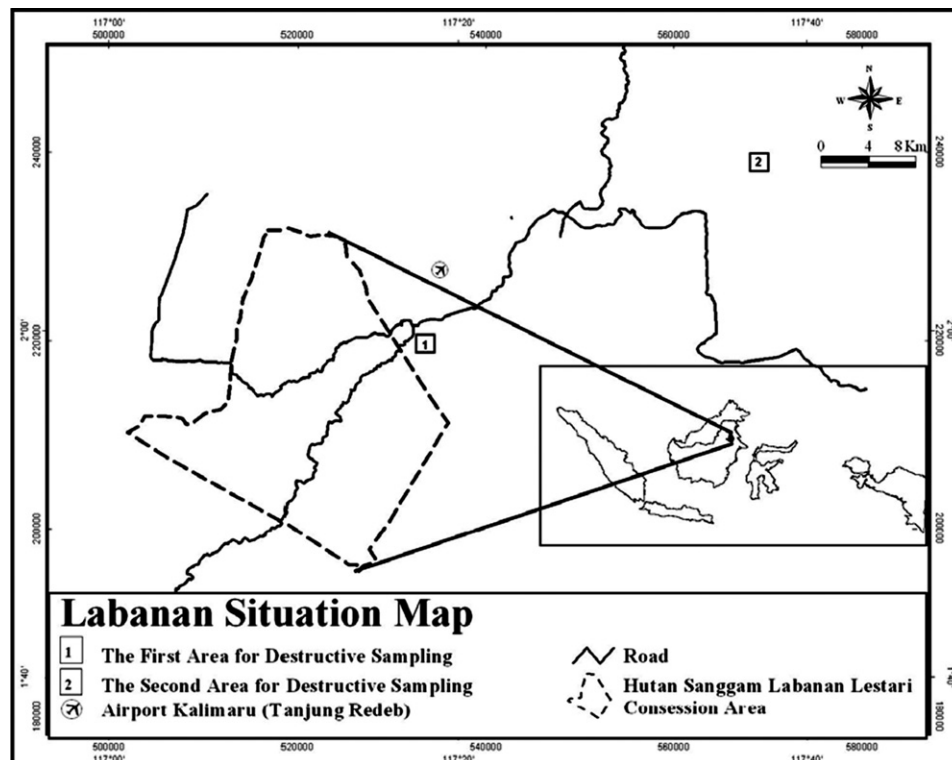

Fig. 1. The locations of the sampling sites in Labanan (the first site) and Merancang (the second site).

dry, while the wet months are from November to May. The rainfall during the dry season remains more than 100 mm per month. The temperature ranges from 21 to 34 °C and the mean is 26 °C (BFMP, 1999).

At the Labanan study area, the dominant soil types are red yellow podzolic or ultisols. However, the soil properties within a soil type vary according to the terrain conditions. Minor soil types include oxisols, vertisols and inceptisols (Mantel, 1999). As in Labanan, the dominant soil of the Merancang study area is red yellow podzolic (66%), and the remainder is Alluvial.

2.2. Data collection

Trees selection was based on species grouping according to Gunawan and Rathert (1999), the inventory data of the concessioners, and a ground check. Forest inventories were conducted within 83,240 ha of the areas managed by PT Hutan Sanggam Labanan Lestari and 51,000 ha of the areas managed by PT Puji Sempurna Raharja. To obtain the representative tree samples, diameter distributions and the species grouping were taken into account during tree selection. The data were collected twice: the first data set was collected in March to April 2006, and the second data set was collected in September to October 2006. The first data set consisted of four commercial genera including *Dipterocarpus* (20 trees, five species), *Hopea* (20 trees, three species), *Palaquium* (19 trees, three species) and *Shorea* (24 trees, nine species). The first data set was collected in Labanan and Puji Sempurna Raharja concession areas, Merancang. The second data set was collected in Labanan, covering commercial (excluding the four mentioned genera) and non-commercial species that consisted of 39 trees from 27 species (Samalca, 2007). These two data sets were used for destructive sampling. The diameters were 6.5–135 cm, 6.5–87 cm, 6.3–74 cm, 6.5–200 cm, and 6–68.9 cm for *Dipterocarpus*, *Hopea*, *Palaquium*, *Shorea* and the second data set, respectively. The overall DBH distributions were: >6–20 cm, 29 trees, >20–40 cm, 36 trees, >40–60 cm, 28 trees, >60–80 cm, 12 trees, >80–100, 9 trees, >100–120 cm, 5 trees and >120–200 cm, 3 trees.

Before conducting the destructive sampling, the DBH was measured. Generally the DBH was measured at 1.30 m above-ground, but for trees with enlargement or buttresses, the diameter was measured at 30 cm above the main enlargement (FAO, 2004). After felling, the tree height was measured. Diameter was measured at 2 m intervals for the stems and big branches with the diameters of more than 15 cm. In addition, the stump height and its diameter were also measured. These measurements were used to estimate the volume and dry weight. The volume of each section was calculated using Smalian's formula as cited by De Gier (2003). The total volume was obtained by summing the volume of each section. Due to the difference in moisture content, the tree material was partitioned into leaves, twigs (diameter <3.2 cm), small branches (diameter 3.2–6.4 cm), large branches (diameter >6.4 cm) and stem (Ketterings et al., 2001). The fresh weight of the leaves, twigs, branches and stems with the diameters equal or less than 15 cm were weighed in the field using spring weighing scales of 50 and 25 kg capacity with accuracy ±1%. A table scale was used to weigh smaller specimens. The latter balance had a capacity of 2000 g with accuracy ±0.5%.

The samples from the partitioned trees were taken in three replications and stored in sealed plastic bags, and then sent to the laboratory to determine their moisture content. In the laboratory, an analytical balance with capacity of 420 g and accuracy of 0.001 g was used to weigh the samples. Dry weights were obtained by drying the samples at a temperature of 105 °C until a constant weight was achieved (Stewart et al., 1992; Ketterings et al., 2001).

To determine the wood density, samples were taken from the lower, middle and upper parts of the stems. The samples were taken as a pie shape or cylinder, so the inner and outer parts of the

trunks with their barks were included (Nelson et al., 1999). Wood density was measured by the water replacement method. To avoid shrinkage during volume measurement, the samples were first saturated. In so doing, rehydration was conducted for 48 h. The volume of each sample was determined from the volume of the water displaced when submerged. The wood density was calculated as dry oven weight divided by saturated volume. The results for the individual specimens are presented in Appendix A.

The dry weight of the stumps, stems, and branches with the diameter of >15 cm was calculated by multiplying the fresh volume of each section by wood density. For the other partitioned trees, the dry weight was calculated through fresh weight multiplied by dry weight/fresh weight ratio of the corresponding samples. The total dry weight of a tree was obtained by summing the dry weight of the stump, stem, branches, twigs, and leaves.

2.3. Data analysis

Based on the data collected, several equations were developed. Firstly, the equations were developed for four individual genera *Dipterocarpus*, *Hopea*, *Palaquium* and *Shorea*. Secondly, these four genera were mixed to develop an equation for commercial species. Finally, the four genera together with the second data set (Samalca, 2007) were used to develop an allometric equation of mixed species.

Before establishing the allometric equation, scatter plots were used to see whether the relationship between independent and dependent variables was linear. Furthermore, several allometric relationships between independent and dependent variables were tested. The independent variables included DBH, CBH, and wood density, whereas the dependent variable was the dry weight of the TAGB. Because the data exhibited heteroscedasticity, a power function was an inappropriate model in this study, so we transformed the data for linear regression using a natural logarithm. The transformation equalized the variance over the entire range of biomass values which satisfies the prerequisite of linear regression (Sokal and Rohlf, 1995; Sprugel, 1983). However, this transformation introduced a systematic bias in the calculation which was corrected using a correction factor (CF) when back-transforming the calculation into biomass (Chave et al., 2005; Sah et al., 2004; Son et al., 2001; Sprugel, 1983).

Model comparison and selection were based on average deviation (Brand and Smith, 1985; Cairns et al., 2003; Chave et al., 2005; Nelson et al., 1999), slope coefficient of the regression (Nelson et al., 1999), Akaike Information Criterion (AIC) (Burnham and Anderson, 2002; Chave et al., 2005), confidence interval (CI) of the predictions, and paired *t*-test. Coefficients of determination (r^2) more than 90% are reported in this paper.

The average deviation was computed from the absolute difference between predicted and observed dry weight and expressed as the percentage of observed dry weight, then all deviations were averaged (Brand and Smith, 1985; Cairns et al., 2003; Chave et al., 2005; Nelson et al., 1999). The equation to calculate average deviation is shown in Eq. (1). The deviation was calculated after the prediction was back-transformed to the unit values and corrected using a CF. The average deviation has been calculated as follows:

$$\bar{S}(\%) = \frac{100}{n} \sum_{i=1}^{n} \frac{|\hat{Y}_i - Y_i|}{Y_i} \tag{1}$$

where $\bar{S}$ is the average deviation, Y_i = the observed dry weight, $\hat{Y}_i$ = the predicted dry weight, n = number of observations.

The formula of AIC used as the criterion for model selection (Chave et al., 2005) is:

$$\text{AIC} = -2\ln(L) + 2p \tag{2}$$

where L is the likelihood of the fitted model and p is the total number of parameters in the model. The optimal model will minimize the AIC value (Chave et al., 2005). AIC is used to compare non-nested models.

2.4. Comparing the equations to previously published equations

The proposed mixed species model was applied to the data of Ketterings et al. (2001). Besides that, we also employed the models of Brown (1997), one of the pan-tropic equations of Chave et al. (2005), and Ketterings et al. (2001) to the current data.

The allometric equation developed by Brown (1997) for tropical moist forest is:

$$TAGB = \exp(-2.134 + 2.53 \ln(DBH)), \tag{3}$$

where TAGB is total above-ground biomass in kg/tree and DBH is in cm. The equation of Brown (1997) was constructed from the data collected by several authors from different tropical countries and at different times. The diameters used to establish this equation ranged from 5 to 148 cm, and the number of sample trees was 170. Besides the model of Brown (1997), one of the pan-tropic models of Chave et al. (2005) was chosen as a comparison of the proposed models. Pan-tropic models were developed from various tropical forests based on the compilation of data since 1950s from 27 study sites in America, Asia and Oceania (Chave et al., 2005). The samples were collected from 2410 trees with DBH that ranged from 5 to 156 cm. The best pan-tropic model for moist tropical forest based on DBH measurements and wood density was applied to the current data. The equation is:

$$TAGB = \rho \exp(-1.499 + 2.148 \ln(DBH) + 0.207(\ln(DBH))^2$$
$$- 0.0281(\ln(DBH))^3) \tag{4}$$

where ρ = species-specific wood density (g/cm^3). In addition to the models mentioned above, the model of Ketterings et al. (2001) was chosen. Ketterings' data consisted of 29 trees from 14 genera with the diameters ranging from 7.6 to 48.1 cm. The allometric equation developed by Ketterings et al. (2001) is:

$$TAGB = r \, \rho^{avg}(DBH)^{2+c} \tag{5}$$

where r is a parameter that is constant over wide range of geographical areas, ρ^{avg} is the average wood density for the study areas, and c is a parameter estimated from relationship between tree height and DBH. For the study areas, c is 0.397, ρ is 0.604 g/cm^3, and r is 0.11.

3. Results

3.1. Developing allometric equations

The model initially developed is presented in Eq. (6):

$$\ln(TAGB) = c + \alpha \ln(DBH) \tag{6}$$

where TAGB is in kg/tree, DBH is in cm, c is the intercept, and α is the slope coefficient of the regression. The values of the coefficients
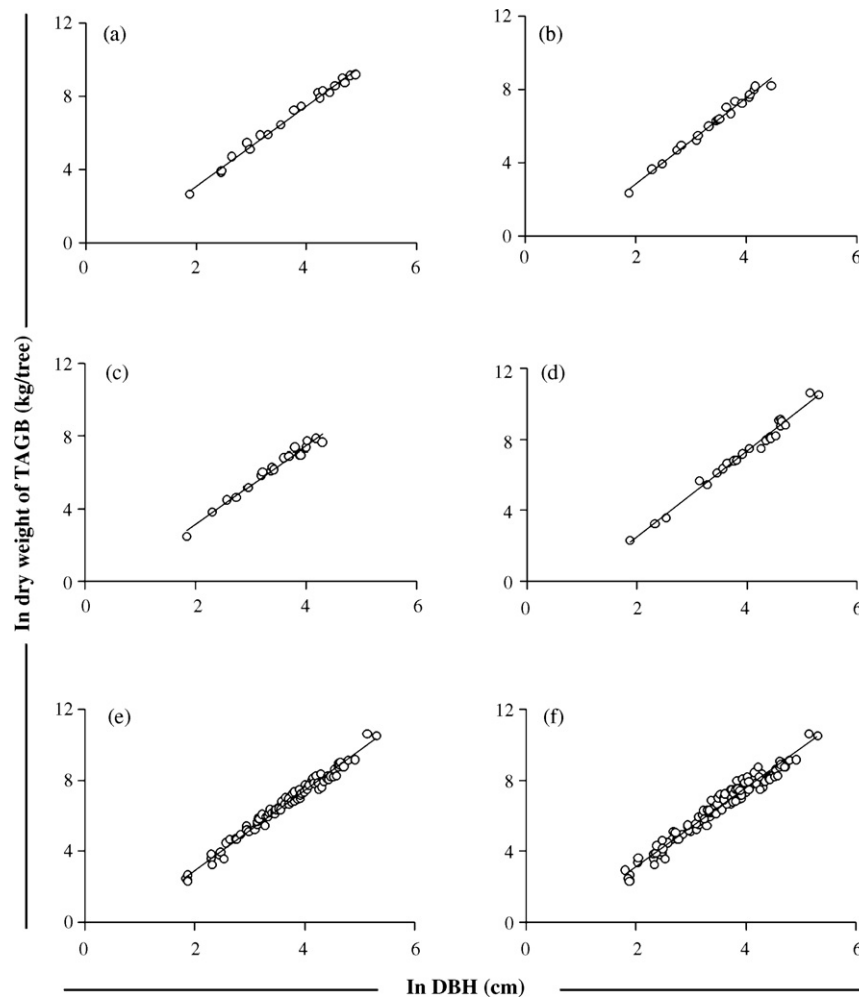
Fig. 2. The linear regression of natural log transformation of DBH (cm) and total above-ground biomass (TAGB) (kg/tree) of *Dipterocarpus* (a), *Hopea* (b), *Palaquium* (c), *Shorea* (d), commercial species (e) and mixed species (f). The number of trees for every regression is 20, 20, 19, 24, 83 and 122, respectively.

are presented in Table 1 and the regression lines are presented in Fig. 2. For this model, the adjusted r^2 ranged from 0.963 to 0.989 and the lowest was found for mixed species. The average deviation was therefore the highest for the mixed species. Among the genera, Shorea had the highest average deviation (19.6%). The allometric equation for every genus, commercial species, and mixed species had a significant slope coefficient at $p < 0.001$ (Table 1).

Model 1 uses only DBH as a predictor. In fact, tree biomass is affected by its height and wood density as well. Therefore, CBH and wood density were incorporated as additional independent variables. Even though measuring the total tree height was easy for felled trees, CBH was used instead of total height due to the practical difficulty of measuring standing trees in the field and the properties of the tree architecture in the study areas. Regarding tree architecture, the bulk of tree biomass measured in the field was in the form of main stems and not in branches and leaves. It accounted of 45–90% with the average of 67% of the TAGB. By incorporating CBH (in meters) as the second predictor in model 2, the model becomes a multiple linear regression as follows:

$$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{CBH}) \tag{7}$$

Since correlation between DBH and TAGB has been high, the addition of CBH in model 2 only increased slightly r^2 and also reduced slightly the average deviation. Table 1 shows that at the genus level, the β coefficients from the inclusion of CBH are significant at $p < 0.05$ for Dipterocarpus and Hopea, and not statistically significant for Shorea (Table 1).

As mentioned above, wood density is an important factor when calculating biomass (Baker et al., 2004; Chave et al., 2005; Nogueira et al., 2007), so it was added as a predictor variable.

Table 1
Model description for the estimation of the total above-ground biomass of Dipterocarp forests.

Species grouping	N	Allometric equation	Coefficient		Standard error of the coefficient	Adjusted r^2	Standard error of residual	Average deviation (%)	CF
			Symbol	Value					
Dipterocarpus	20	$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH})$	c	−1.232***	0.200	0.989***	0.210	18.65	1.022
			α	2.178***	0.053				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{CBH})$	c	−2.187***	0.428	0.992***	0.183	14.15	1.017
			α	2.007***	0.084				
			β	0.575*	0.236				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{WD})$	c	−1.190**	0.336	0.989***	0.213	18.84	1.023
			α	2.175***	0.057				
			β	0.082ns	0.488				
Hopea	20	$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH})$	c	−1.813***	0.213	0.987***	0.184	14.08	1.017
			α	2.339***	0.061				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{CBH})$	c	−2.856***	0.480	0.990***	0.165	12.76	1.014
			α	2.116***	0.109				
			β	0.656*	0.277				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{WD})$	c	−1.708***	0.301	0.987***	0.188	13.87	1.018
			α	2.335***	0.063				
			β	0.174ns	0.344				
Palaquium	19	$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH})$	c	−1.098***	0.281	0.975***	0.230	18.78	1.027
			α	2.142***	0.082				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{CBH})$	c	−1.663***	0.275	0.984***	0.181	13.72	1.017
			α	1.817***	0.114				
			β	0.612**	0.177				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{WD})$	c	−0.723*	0.286	0.980***	0.201	16.86	1.020
			α	2.145***	0.071				
			β	0.704*	0.273				
Shorea	24	$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH})$	c	−2.193***	0.253	0.984***	0.2601	20.49	1.034
			α	2.371***	0.063				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{CBH})$	c	−2.758***	0.417	0.985***	0.250	18.60	1.032
			α	2.178***	0.131				
			β	0.463ns	0.277				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{WD})$	c	−1.533***	0.405	0.986***	0.244	19.14	1.030
			α	2.294***	0.070				
			β	0.560ns	0.278				
Commercial species	83	$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH})$	c	−1.498***	0.127	0.981***	0.252	21.61	1.032
			α	2.234***	0.034				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{CBH})$	c	−2.266***	0.213	0.985***	0.227	18.63	1.026
			α	2.030***	0.056				
			β	0.542***	0.125				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{WD})$	c	−1.045***	0.150	0.985	0.225	18.77	1.057
			α	2.203***	0.031				
			β	0.639***	0.138				
Mixed species	122	$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH})$	c	−1.201***	0.141	0.963	0.335	30.32	1.058
			α	2.196***	0.039				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{CBH})$	c	−1.935***	0.234	0.967***	0.318	27.49	1.052
			α	1.981***	0.067				
			β	0.541***	0.141				
		$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{WD})$	c	−0.744***	0.154	0.970***	0.303	26.51	1.047
			α	2.188***	0.035				
			β	0.832***	0.157				

Note: The statistical analyses are significant at 95% confidence interval. ***$p < 0.001$; **$p < 0.01$; *$p < 0.05$; and non-significant, ns$p > 0.05$. N; the number of tree samples, TAGB; total above-ground biomass based on dry weight (kg/tree), DBH: diameter at breast height (cm), CBH: commercial bole height (m), WD: wood density (g/cm^3), and CF: correction factor.

Adding wood density in the model is important in order to estimate the biomass for mixed species and big trees, since biomass estimates for larger DBH trees are more variable and have a disproportionately large contribution to forest biomass.

By incorporating wood density in the third model, the equation becomes:

$$\ln(\text{TAGB}) = c + \alpha\ln(\text{DBH}) + \beta\ln(\text{WD}) \tag{8}$$

where WD is wood density for every measured tree. The β coefficient in model 3 was not statistically significant for *Dipterocarpus*, *Hopea* and *Shorea*, whereas for the commercial and mixed species equations, it was highly significant at $p < 0.001$ (Table 1).

To compare model 2 and 3, AIC was calculated and the results are presented in Table 2. The AIC values for model 3 were lower than that for model 2, except for *Dipterocarpus* and *Hopea*. Based on the species grouping, the highest AIC values were found for the mixed species followed by the commercial species and the lowest were in the genera.

Our estimates of wood densities were compared with the data from GPG and from Plant Resources of South East Asia (PROSEA) (Soerianegara and Lemmens, 1993). The results show that increasing DBH is not followed by an increase in wood density. This finding is in agreement with the previous research by Baker et al. (2004) and Nogueira et al. (2005, 2007). The comparison of the wood density values based on the current study and those from the published data of GPG and PROSEA (Soerianegara and Lemmens, 1993) is presented in Appendix A. In the GPG, for *Shorea* only *Shorea* spp. *balau* group, *Shorea* spp. (dark red meranti), *Shorea* spp. (light red meranti), etc. are mentioned but their species are not. In fact, the commercial timber red meranti consists of many species, such as *S. parvifolia*, *S. smithiana*, *S. macroptera*. The wood density for the dominant species from every genus is superimposed with the wood density from the corresponding species of the published data (PROSEA) and presented in Fig. 3. Two outliers of wood density, indicated by the circles, are found from *Palaquium gutta* of the current data. The first is at a DBH of 50 cm with a wood density of 0.43 g/cm^3, and the second is at a DBH of 28.6 cm with a wood density of 0.76 g/cm^3. The data from the PROSEA are indicated by the rectangular shapes which show the highest and the lowest values of wood densities of *H. cernua* and *P. gutta*.

### 3.2. Comparing the equations to previously published equations

Model 1 of the mixed species regression was applied to the data of Ketterings et al. (2001). The predicted TAGB using the first model to the Ketterings' data produced the same trend as the observed data (Fig. 4).

Table 2
The Akaike Information Criterion (AIC) for model 2 and 3.

Species grouping	Model	AIC
Dipterocarpus	2	321
	3	326
Hopea	2	282
	3	303
Palaquium	2	271
	3	264
Shorea	2	458
	3	437
Commercial species	2	1490
	3	1464
Mixed species	2	2176
	3	2157
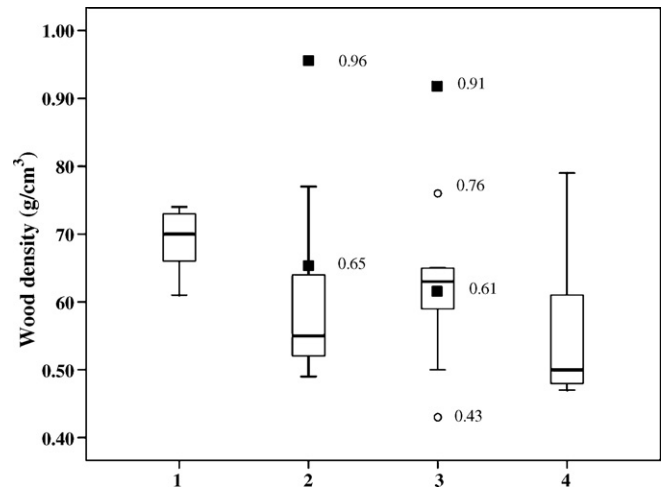
Fig. 3. The wood density of 1: *D. pacyphyllus* ($n = 8$), 2: *H. cernua* ($n = 18$), 3: *P. gutta* ($n = 13$) and 4: *S. retusa* ($n = 6$), the dominant species of *Dipterocarpaceae*, *Hopea*, *Palaquium* and *Shorea*, respectively. The cycle shapes with values of 0.76 and 0.43 are the outlier of *H. cernua* from the current data. The rectangle shapes indicate the highest and the lowest wood density of *P gutta* and *H cernua* from the data of PROSEA.
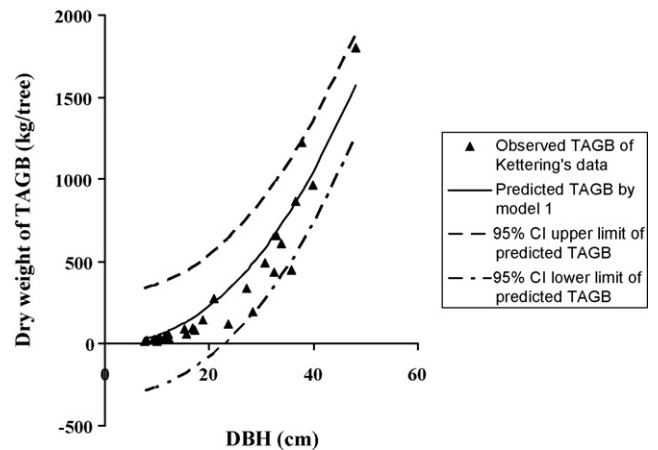
Fig. 4. The regression line in model 1 of the mixed species (122 sample trees) as applied to the published data by Ketterings et al. (2001).
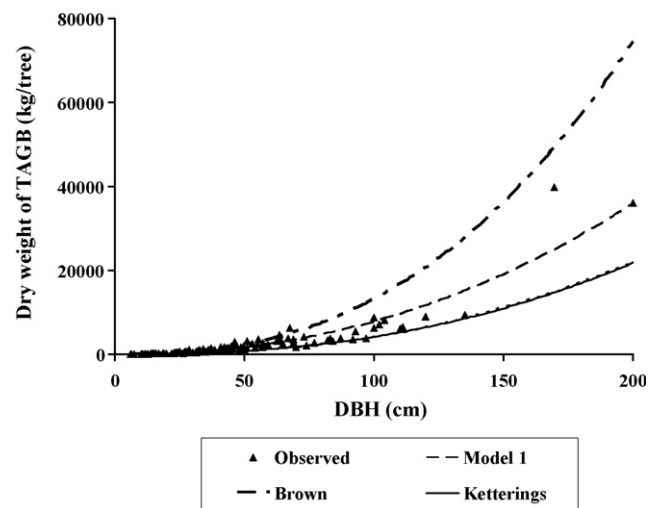
Fig. 5. The DBH versus dry weight of the total above-ground biomass for the mixed species (122 sample trees) from the observed data and the prediction lines using model 1, models of Brown (1997) and Ketterings et al. (2001).

Table 3
The average deviation of various models.

Species grouping	The employed equation	Average deviation ($\bar{S}$)[*](%)
Dipterocarpus	Model 1	18.65
	Model 2	14.15
	Model 3	18.84
	Brown (1997)	62.78
	Chave et al. (2005)	89.67
	Ketterings et al. (2001)	46.81
Hopea	Model 1	14.08
	Model 2	12.76
	Model 3	13.87
	Brown (1997)	42.94
	Chave et al. (2005)	52.08
	Ketterings et al. (2001)	49.46
Palaquium	Model 1	18.78
	Model 2	13.72
	Model 3	16.86
	Brown (1997)	43.94
	Chave et al. (2005)	54.13
	Ketterings et al. (2001)	50.71
Shorea	Model 1	20.49
	Model 2	18.60
	Model 3	19.14
	Brown (1997)	107.16
	Chave et al. (2005)	94.44
	Ketterings et al. (2001)	32.15
Commercial species	Model 1	21.61
	Model 2	18.63
	Model 3	18.77
	Brown (1997)	66.77
	Chave et al. (2005)	73.85
	Ketterings et al. (2001)	44.02
Mixed species	Model 1	30.32
	Model 2	27.49
	Model 3	26.51
	Brown (1997)	51.95
	Chave et al. (2005)	55.09
	Ketterings et al. (2001)	51.89

[*] $\bar{S}(\%) = \frac{100}{n}\sum_{i=1}^{n}|\hat{Y}_i - Y_i|/Y_i$, $\bar{S}$ = average deviation, Y_i = observed values, $\hat{Y}_i$ = predicted values.

The average deviation for individual trees of the previously published models is always higher than that of models 1, 2, and 3 of the mixed species (Table 3). At the genus level, prediction of TAGB using the equation of Brown (1997) resulted average deviation ranging from 43% to 107% and from 52% to 94% for the equation of Chave et al. (2005).

When the equations of Chave et al. (2005) and Brown (1997) were applied to our data, the predicted values were over estimated. In contrast, the model of Ketterings et al. (2001) underestimated the TAGB. This evident can be seen from the CI values presented in Table 4. At 95% CI, upper and lower limit of the mean TAGB from the model of Brown (1997) and Chave et al. (2005) were higher than the observed values. In addition, paired *t*-test presented in Table 5 shows that for one tailed at α = 0.05, the mean of the observed data and the proposed models is significantly different from the predicted mean using the previously published models. Fig. 5 shows the observed values and the prediction line using model 1, model of Brown (1997) and Ketterings et al. (2001).

Table 5
Paired *t*-test at 95% confidence interval of the mean of the total above-ground biomass (kg) for mixed species (122 trees).

Pair	*t*-statistic	Significance (one tailed)
Observed–model of Brown (1997)	−4.184	0.000
Observed–model of Chave et al. (2005)	−4.849	0.000
Observed–model of Ketterings et al. (2001)	4.330	0.000
Model 1–model 2	2.575	0.006
Model 1–model 3	−0.921	0.179
Model 1–model of Brown (1997)	−3.978	0.000
Model 1–model of Chave et al. (2005)	−4.346	0.000
Model 1–model of Ketterings et al. (2001)	6.669	0.000

4. Discussion

4.1. Allometric equations

When the first and the second data sets were used to generate the equations for mixed species, the deviations of the predicted biomass was higher than the observed one. This is due to the higher variation in tree characteristics among those species, and in the genera between the first and the second data set. Based on the raw data, it can be observed that the second data set for the DBH of 6, 36, and 68 cm has dry weights of 19, 1100, and 6300 kg biomass, respectively, whereas for the first data set at those diameters the biomass is 10–14, 900, and 3800 kg, respectively. These results are in agreement with the research of Nelson et al. (1999) who found that by using the same allometric equation with DBH as the independent variable, the deviation in species-specific regressions varies from 10.9% to 14.7% for trees with the diameters from 5.1 to 38.2 cm, but if these species were mixed, the average deviation was 19.8%.

In the equation based on the individual genus, *Hopea* has the lowest average deviation, because the sample of this genus only consists of three species. On the other hand, within the *Shorea* group, the average deviation is the highest because it consists of 10 species and the diameter range is wider (6.5–200 cm).

At the genus level for model 2, the lower significance level of β, when compared to the α coefficient, may be caused by effect of multicollinearity. In a multiple linear regression, multicollinearity causes partial regression coefficients for one or both independent variables to be less precise, and *t*-values to become less significant (Nelson et al., 1999). In the current data, the tolerance values for every genus and mixed species do not indicate multicollinearity. However, based on Pearson correlations between DBH and CBH, it shows a fair correlation for every genus, except *Palaquium*. So, this correlation induces multicollinearity in model 2, but the multi-collinearity is weak because the β coefficient is still significant at $p < 0.05$, except for *Shorea*. Multicollinearity disappears for the allometric equations of commercial and mixed species, because these equations were constructed from a larger number of samples where some of them have weak multicollinearity and the others do not indicate multicollinearity at all.

The role of wood density in the allometric equation is more prominent for the mixed species than in the genera. As presented in Table 1, the β coefficients of commercial and mixed species equations are significant at the 95% CI. The evidence that the variation of wood

Table 4
The confidence interval (CI) of the mean from various models for mixed species (122 trees).

Parameters	Observed	Model 1	Model 2	Model 3	Brown	Chave	Ketterings
Mean TAGB (kg)	2284.21	2416.69	2280.74	2458.60	3832.45	4180.43	1239.39
95% CI Lower limit of mean TAGB (kg)	1376.51	1456.35	1526.76	1570.11	2297.53	2581.58	759.25
95% CI Upper limit of mean TAGB (kg)	3191.90	3377.35	3034.73	3347.09	5367.38	5779.27	1719.25
The number of trees	122	122	122	122	122	122	122

density among the genera is higher than within a single genus is also supported by Baker et al. (2004) and Chave et al. (2006).

The importance of including wood density in biomass estimation can be examined for big trees, such as *Shorea superba* and *Shorea* sp. The *S. superba* with a diameter of 170 cm has a TAGB dry weight of 39.7 tons, whereas the other (*Shorea* sp.) with a diameter of 200 cm has a lower dry weight of TAGB, that is 36 tons. It is likely that the differences in wood density and tree architecture explain the differences in the dry weight of these two species. Although *S. superba* has smaller DBH and shorter CBH, it has higher wood density compared to that of *Shorea* sp., resulting in the same dry weight of commercial bole (27.8 tons). The characteristics of these species show that their wood density, DBH and CBH are 0.86 g/cm³, 170 cm and 26 m for *S. superba*, and for *Shorea* sp., they are 0. 57 g/cm³, 200 cm and 28 m, respectively. In this research, the genus of *Shorea* consists of several big trees, however, adding wood density to the model does not significantly influence β coefficient (Table 1).

The measurements of wood density of different species from the lowland *Dipterocarp* forests can be useful to complement the proposed methodology for estimating carbon stock change. In addition, for several of the species reported here no wood density values have previously been published. In the GPG, only a single value for wood density is given for certain species (see Appendix 3A.1. of GPG). With respect to the GPG methodology for estimating carbon stock change, the major source of uncertainty for estimating carbon stock using the default method is related to the applicability of these parameters for the diverse age and composition structure of specific stands (IPCC, 2003). Thus, the various values of wood density from different characteristics of forests must be considered. As an example, in this study the wood density of *Dipterocarpus grandiflorus* is 0.56 g/cm³ for a DBH of 18.8 cm and 0.75 g/cm³ for a DBH of 44 cm (Appendix A), while in the GPG the wood density of this species is 0.62 g/cm³, without any indication of the diameter.

4.2. Fitting and applicability of the models

Even though most AIC values of model 3 are lower than model 2 (Table 2), the values are relatively the same. Therefore for fitting the models, the emphasis will be given more on the coefficient of the regression, average deviation, the range of CI, and paired *t*-test. Of the proposed models, model 1 gives a better prediction than model 2. This can be observed from the inclusion of CBH into the model. It increases r^2 slightly and the average deviation decreases slightly, but the slope less significant and the standard error of α coefficient also increases. Based on the lower and upper limit CI of the mixed species, model 1 is closer to the range of the mean of the observed values (Table 4). In contrast, the upper and lower limit of CI of model 2 does not reach the range of CI of the observed values. For the mixed species, model 1 is significantly different from model 2 (Table 5). Model 1 is therefore the preferred model for estimating the TAGB of *Dipterocarp* forests.

Within the genus, model 3 does not give effect over model 1 since β coefficient does not significantly influence the model (Table 1). However, adding wood density as a predictor is an alternative to estimate the biomass of big trees and mixed species. The β coefficient is significant when wood density is incorporated into mixed species and the average deviation decreases. The effect of wood density to the dry weight is evident for big trees from the current data set as explained previously and from the different data set of Brown as explained in the next paragraph.

A possible explanation for higher prediction when applying the model of Brown (1997) and Chave et al. (2005) to the current data is the deference in wood density and tree architecture. Although, some of Brown's and Chave's data were collected in Kalimantan, it does not imply that the characteristics of the trees from

Kalimantan, as used by Brown (1997) and Chave et al. (2005), are the same as the trees used in this study. As can be seen from Brown's data, one of the trees from Kalimantan with the diameter of 130 cm had dry weight of 42.8 tons (Brown, 1997), whereas from the current research, *Shorea* sp. with a diameter of 200 cm has dry weight of 36 tons. However, the prediction line of Ketterings' equation lies below the observed values and the prediction line of model 1 (Fig. 5). This may be caused by the marked difference between the sampled trees in this study and Ketterings' data. The only species which are found both in Ketterings' data and this study are *Shorea* and *Alseodaphne,* sp. The lower prediction of Ketterings' equation is because the trees used to construct Ketterings' equation were much smaller than those from the current study, as elaborated in the previous section. In addition to the explanations above, the inclusion of wood density in assessing biomass carbon will reduce uncertainty due to the variation among differences of sites (Chave et al., 2006; Baker et al., 2004).

Based on the application of the proposed model and the previously published data, for an accurate biomass estimation, one must consider site specific equations. This finding is supported by Cairns et al. (2003) and Nelson et al. (1999) when they apply a previously published equation to their data. Nelson et al. (1999) overestimated biomass prediction by 10–60% for trees with a DBH from 5 to 25 cm, and showed an even greater over-estimation for trees with larger DBH. In contrast with these results, Chave et al. (2005) and Gibbs et al. (2007) stated that for tropical forests, local species-specific allometric equations are not needed; instead, generalized allometric relationships must be employed. Moreover, grouping species by broad forests types or ecological zones is highly more effective than generating allometric equations for local conditions or species-specific allometric equations, because the local equations will not improve accuracy significantly. However, based on the analysis of the 95% CI of the mean, the prediction using the pan-tropic allometric equation by Chave et al. (2005) showed that the lower limit of the prediction is much higher than the observed values (Table 4). The lower boundaries of the observed data, the prediction using model 1, and the prediction using pan-tropic model are 1376.5, 1456.3, and 2581.6, respectively. The average deviations of the lower limit CI of these two predictions from the observed data are 6% and 87%.

Paired *t*-test presented in Table 5 supports the CI discussed above. At 95% CI, the mean of the observed and the proposed models are significantly lower than the mean of the models of Brown (1997) and Chave et al. (2005), but higher compared to that of Ketterings et al. (2001).

With regards to GPG (Appendix 4A.2), the developed model can be used to complement the existing equations by Brown which are used in GPG.

4.3. Sources of error

In developing the equations in this study several potential sources of errors could be identified:

- Wood density differs among the tree sections: it is higher at breast height than at the top of bole (Nogueira et al., 2005) and also higher at the base of the tree stem than that at the base of the living crown (Cordero and Kanninen, 2002). In the current study, the samples for wood density analysis were taken from the upper, middle and lower of the main trunk. However, these data were also used to estimate the weight of the big branches that were impossible to be weighed. This causes over-estimation of the weight for individual trees.
- The number of species for developing the allometric equations may not be enough to represent the gamut of species present at the study areas. Based on the data from 90 plots of 500 m²,

Wahyuningum (2005) found 124 species in Labanan, whereas in this study, only 47 species were used.

- The majority of samples had a diameter of less than 120 cm; there were only 3 trees with a diameter of more than 120 cm, which were 135, 170 and 200 cm. Ideally, there should be several trees which have diameters between 135 and 200 cm for developing mixed species equation.

5. Conclusion

Model 1, $\ln(\text{TAGB}) = c + \alpha \ln(\text{DBH})$, is the most suitable allometric equation for *Dipterocarp* forests. The range of 95% CI of model 1 is closer to the observed values, so it can be applied to studies of the carbon balance. This allometric equation can be used to improve and complement the GPG, especially for tropical forests that are dominated by *Dipterocarp* species. In addition, model 3 is

an alternative model since wood density is an important factor for estimating the biomass for mixed species.

Diameter is the only explanatory variable in model 1, it is easy to measure and generally available in standard forest inventory. The inclusion of CBH into DBH as predictor variable does not improve the performance of model 1.

Based on the application of the proposed model to the previously published data and the application of the published equation to the current data, it can be concluded that the application of site specific equation must be considered.

Acknowledgement

Appendix A. The wood density of the current study and the published data

No.	Species	This research		GPG-LULUCF[**]		PROSEA[**]	
		Diameter (cm)	WD[*] (g/cm³)	Diameter (cm)	WD[*] (g/cm³)	Diameter (cm)	WD[*] (g/cm³)
1	*Dipterocarpus convertus*	11.5	0.52				
2	*D. crinitus*	83.0	0.65				0.740–1.070
3	*D. crinitus*	104.0	0.77				
4	*D. grandiflorus*	18.8	0.64		0.62		0.650–0.945
5	*D. grandiflorus*	44.0	0.75				
6	*D. grandiflorus*	49.5	0.62				
7	*D. humeratus*	14.0	0.54				0.730–0.800
8	*D. humeratus*	27.0	0.69				
9	*D. pacyphyllus*	34.0	0.70				
10	*D. pacyphyllus*	67.0	0.73				
11	*D. pacyphyllus*	69.0	0.70				
12	*D. pacyphyllus*	73.0	0.61				
13	*D. pacyphyllus*	93.0	0.74				
14	*D. pacyphyllus*	111.0	0.66				
15	*D. pacyphyllus*	120.0	0.66				
16	*D. pacyphyllus*	135.0	0.73				
17	*D. palmbanicus*	6.5	0.67				0.595–0.785
18	*D. palmbanicus*	11.8	0.78				
19	*D. palmbanicus*	19.8	0.65				
20	*D. palmbanicus*	23.5	0.70				
21	*Hopea cernua*	6.5	0.65				0.650–0.960
22	*H. cernua*	10.0	0.57				
23	*H. cernua*	11.8	0.49				
24	*H. cernua*	15.5	0.51				
25	*H. cernua*	17.0	0.67				
26	*H. cernua*	22.0	0.52				
27	*H. cernua*	23.0	0.64				
28	*H. cernua*	28.0	0.55				
29	*H. cernua*	31.5	0.55				
30	*H. cernua*	32.5	0.66				
31	*H. cernua*	34.0	0.54				
32	*H. cernua*	38.5	0.54				
33	*H. cernua*	41.0	0.51				
34	*H. cernua*	45.0	0.77				
35	*H. cernua*	51.0	0.56				
36	*H. cernua*	57.0	0.53				
37	*H. cernua*	59.0	0.58				
38	*H. cernua*	64.0	0.51				
39	*H.dryobalanoides*	62.4	0.69				0.480–0.980
40	*H. mengrawan*	87.0	0.66				0.510–0.980
41	*Palaquium gutta*	10.0	0.50				0.610–0.910
42	*P. gutta*	19.0	0.65				
43	*P. gutta*	24.0	0.65				
44	*P. gutta*	28.6	0.76				
45	*P. gutta*	29.0	0.65				
46	*P. gutta*	30.0	0.61				
47	*P. gutta*	36.0	0.61				
48	*P. gutta*	40.5	0.65				
49	*P. gutta*	48.0	0.59				
50	*P. gutta*	50.0	0.43				
51	*P. gutta*	54.0	0.63				
52	*P. gutta*	55.0	0.53				

Appendix A (*Continued*)

No.	Species	This research		GPG-LULUCF[**]		PROSEA[**]	
		Diameter (cm)	WD[*] (g/cm^3)	Diameter (cm)	WD[*] (g/cm^3)	Diameter (cm)	WD[*] (g/cm^3)
53	*P. gutta*	65.0	0.63				
54	*P. rostratum*	6.3	0.56				0.480–0.760
55	*P. rostratum*	15.8	0.58				
56	*P. rostratum*	25.0	0.62				
57	*P. rostratum*	45.0	0.67				
58	*Palaquium* sp.	13.0	0.44				
59	*Palaquium* sp.	74.0	0.38				
60	*Shorea agamii*	100.0	0.50				0.665
61	*S. atrinervosa*	50.0	0.60				0.770–1.110
62	*S. atrinervosa*	100.0	0.71				
63	*S. macroptera*	23.0.0	0.54				0.370–0.770
64	*S. macroptera*	45.0	0.48				
65	*S. parvifolia*	31.5	0.51				0.290–0.835
66	*S. parvifolia*	57.0	0.52				
67	*S. parvifolia*	102.0	0.61				
68	*S. parvifolia*	110.0	0.60				
69	*S. parvistipulata*	35.0	0.45				
70	*S. retusa*	26.5	0.50				
71	*S. retusa*	70.0	0.48				
72	*S. retusa*	77.0	0.61				
73	*S. retusa*	84.0	0.47				
74	*S. retusa*	92.0	0.50				
75	*S. retusa*	97.0	0.79				
76	*S. smithiana*	10.2	0.32				0.300–0.720
77	*Shorea* sp.	6.5	0.55				
78	*Shorea* sp.	12.5	0.39				
79	*Shorea* sp.	38.1	0.50				
80	*Shorea* sp.	43.0	0.54				
81	*Shorea* sp.	82.0	0.38				
82	*Shorea* sp.	200.0	0.57				
83	*S. superba*	170.0	0.86				0.695–1.095
	Shorea spp., balau group				0.70		
	Shorea spp., dark red meranti				0.55		
	Shorea spp., light red meranti				0.40		
	Shorea spp., white meranti				0.48		
	Shorea spp., yellow meranti				0.46		

[*] Wood density (g/cm^3), and for this research it is expressed as oven dry weight (g) per saturated volume (cm^3).
[**] Published data.

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