

FORM FACTORS AND VOLUME MODELS FOR ESTIMATING TREE BOLE VOLUME OF MAHOGANY AT COMMUNITY FORESTS IN CENTRAL JAVA

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FORM FACTORS AND VOLUME MODELS FOR ESTIMATING TREE BOLE VOLUME OF MAHOGANY AT COMMUNITY FORESTS IN CENTRAL JAVA. Form factors and volume models are often be used in the estimation of tree volumes. However, a few studies have developed and evaluated the accuracy of form factors and volume models for estimating tree volumes of community forests. This study aimed to formulate form factors and volume models and assess their prediction accuracy for estimating tree bole volumes of mahogany at community forests in Central Java. This study used 120 sample trees with diameters of 6–38 cm to formulate artificial and absolute form factors and to develop tree bole volume models. These form factors coupled with bole height and total height were used in simple volume equations. Regression analyses were used to develop volume models using the diameter and total height as predictors. The simple volume equations and volume models' prediction accuracy was evaluated using a cross-validation dataset and independent dataset (30 sample trees). The artificial form factor (0.68 ± 0.11) of mahogany, which was higher than the absolute form factor (0.46 ± 0.09), provided accurate estimates of tree bole volumes when it was used with the bole height instead of the total height. The volume model that uses diameter and total height produced the most accurate estimates, while the volume model that uses diameter alone provided the most practical yet reliable tool for estimating tree bole volumes of mahogany. The results of this study are useful for improving community forest management.

Keywords: Form factor, tree bole, tree volume, mahogany, Central Java

FAKTOR BENTUK DAN MODEL VOLUME UNTUK PENDUGAAN VOLUME BATANG POHON MAHONI PADA HUTAN RAKYAT DI JAWA TENGAH. Faktor bentuk dan model volume sering digunakan untuk pendugaan volume pohon. Akan tetapi, masih sedikit penelitian yang mengembangkan dan mengevaluasi akurasi faktor bentuk dan model volume untuk pendugaan volume pohon di hutan rakyat. Penelitian ini bertujuan memformulasikan faktor bentuk dan model volume serta menilai akurasi untuk menduga volume batang pohon mahoni pada hutan rakyat di Jawa Tengah. Penelitian ini menggunakan 120 pohon contoh berdiameter 6–38 cm, untuk memformulasikan faktor bentuk buatan dan faktor bentuk absolut serta menyusun model-model volume batang pohon. Faktor-faktor bentuk beserta tinggi pangkal tajuk dan tinggi total digunakan dalam persamaan volume sederhana. Analisis regresi digunakan untuk menyusun model-model volume menggunakan diameter dan tinggi total sebagai peubah penduga. Akurasi pendugaan dari persamaan volume sederhana dan model-model volume dievaluasi menggunakan data validasi silang dan data terpisah (30 pohon contoh). Faktor bentuk buatan pohon mahoni ($0,68 \pm 0,11$), yang lebih tinggi daripada faktor bentuk absolut ($0,46 \pm 0,09$), memberikan nilai-nilai dugaan volume pohon yang akurat jika digunakan bersama tinggi pangkal tajuk daripada tinggi total. Model-model volume yang menggunakan diameter dan tinggi total menghasilkan nilai-nilai dugaan yang paling akurat, sedangkan model volume yang hanya menggunakan diameter paling praktis namun dapat diandalkan untuk pendugaan volume batang pohon mahoni. Hasil penelitian bermanfaat untuk perbaikan pengelolaan hutan rakyat.

Kata kunci: Faktor bentuk, volume batang, volume pohon, mahoni, Jawa Tengah

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I. INTRODUCTION

Estimation of timber volume is a common practice of forest managers to assess the economic benefits of their forests, not only at large scale industrial forests but also at small scale community forests. In many parts of Java, Indonesia, communities manage their forests for producing timber that is traded to fulfil their urgent needs, such as covering expenses for children's school and traditional ceremonies (Nugroho & Tiriyana, 2013). While communities have good knowledge and skills related to silvicultural aspects (e.g. species selection, planting, and tending) of community forests, their knowledge and skills on estimating timber volume need to be improved (Soedomo, 2014). A common practice in selling timber from a community forest is that an owner seeks and lets a middleman conduct an economic valuation of standing trees without knowing the actual volume of the standing trees. Unfortunately, the middleman only relies on his/her judgement and experience in valuing the standing trees instead of using an appropriate tree volume estimation tool. Such a selling practice could provide an unreliable way of estimating tree volumes, resulting in a profit loss for community forest owners (Ardelina, Tiriyana, & Muhdin, 2015).

To support a good practice of community forest management, simple yet reliable tools for estimating tree volumes need to be developed for various types of plantations and sites. Community forests in Java are diverse in terms of tree species, site conditions, and silvicultural treatments. Some communities might perform silvicultural treatments (e.g. fertilizing, weeding, and pruning) to their forests, but some other communities might not perform any silvicultural treatments (Kallio, Krisnawati, Rohadi, & Kanninen, 2011; Nugroho & Tiriyana, 2013). This would have resulted in high variability in timber volume even for a certain tree species under different site conditions and silvicultural treatments. Therefore, the development of estimation tools for timber volume of

community forests should be species- and site-specific.

Standing tree volumes can be estimated using simple volume equations or volume models (Ardelina et al., 2015; dos Reis et al., 2019; Husch, Beers, & Kershaw, 2003; Philip, 1994; Santos, Terra, Chaer, & Monte, 2019). The simple volume equation is a cylindrical formula that uses diameter, height, and form factor to account for tapered stem shape (Husch et al., 2003). While the diameter and height are measured in the field, the form factor is determined based on a preliminary study on stem shape. Tree species may have different form factors because of differences in tree architectures among species (Colgan, Swemmer, & Asner, 2014; Tenzin, Wangchuk, & Hasenauer, 2016). A species-specific form factor is therefore required to estimate tree volumes using the simple volume equation accurately. However, the need for reliable form factors could be eliminated when the estimation of tree volumes uses a volume model. Commonly, a volume model uses diameter and height to estimate tree volumes through a regression equation (Magnussen, Kleinn, & Fehrmann, 2020; Santos et al., 2019). In some cases, the volume model might use only the diameter when height strongly correlates with diameter, making the volume model easier to use than the simple volume equation.

Numerous volume models have been developed for various tree species of natural and plantation forests in Indonesia (Krisnawati, Adinugroho, & Imanuddin, 2012). Still, only a few volume models were available for community forests. To our knowledge, the published volume models for community forests were available for the following species and locations: small-leaved mahogany (*Swietenia mahagoni*) in Purworejo Regency, Central Java (Purwanto & Widayanti, 2008); teak (*Tectona grandis*) in Gunung Kidul Regency, Central Java (Purwanto & Kurniasari, 2009); pulai (*Alstonia scholaris*) in Musi Rawas Regency, South Sumatera (Sumadi, Nugroho, & Rahman, 2010);

teak in Klungkung Regency, Bali (Susila, 2012); jabon (*Anthocephalus cadamba*) in Banjarnegara Regency, Central Java (Yulianti, 2012); weru (*Albizia procera*) in Majalengka Regency, West Java (Bustomi & Yulianti, 2014); and sengon (*Falcataria moluccana*) in Bogor Regency, West Java (Ardelina et al., 2015). Thus, further developments of species- and site-specific volume models are beneficial to support management of community forests in various regions of Indonesia.

When an appropriate volume model was not available for a certain region, a reasonable option for communities to estimate tree volumes is using a simple volume equation. However, the accuracy of a simple volume equation could be questioned when it is compared to that of a volume model. Among the previously mentioned studies on developing volume models for community forests, only Ardelina et al. (2015) evaluated further and compared the simple volume equation and volume model accuracy. Ardelina et al. (2015) confirmed that the simple volume equation was less accurate than the volume model for estimating tree volumes of sengon (*F. moluccana*). While Ardelina et al. (2015) also confirmed that the accuracy of simple volume equation depended on the choice of form factors, but they did not investigate whether tree height (e.g. total height or bole height) would affect the accuracy of a simple volume equation. Similarly, Pereira et al. (2020) did not investigate the effect of tree height on the accuracy of simple volume equation, while they evaluated the accuracy of form factor and form quotient.

Empirical studies, therefore, are required to evaluate the choice of appropriate form factors and heights on the accuracy of simple volume equation with a comparison to the accuracy of volume model. In the present study, this issue is further investigated by using a case study in a community forest dominated by big-leaved mahogany (*Swietenia macrophylla*) in Central Java. Specifically, our objectives were threefolds: 1) to formulate appropriate form factors and volume models for mahogany trees, 2) to assess

the accuracy of simple volume equation and volume models in estimating tree bole volumes of mahogany, and 3) to recommend appropriate options for estimating tree bole volumes of mahogany at community forests. This study focussed on estimating the bole volumes of mahogany because they are commonly traded by communities, particularly in the study area.

II. MATERIAL AND METHOD

A. Study Area

This study was conducted at community forests in Klirong District of Kebumen Regency, Central Java. In this district, big-leaved mahogany (hereafter called mahogany) stands were mostly planted by communities on their lands (gardens and home-yards) in three villages: Tanggulangin, Jerukagung, and Jogosimo. The mahogany stands in Tanggulangin Village were dominated by large trees (diameter of 16.7 ± 8.5 cm), while those in Jerukagung and Jogosimo villages were dominated by medium trees (diameter of 11.4 ± 6.4 cm) and small trees (diameter of 8.8 ± 5.2 cm), respectively. Mahogany is preferred by the communities of those villages because of its high timber price and site suitability compared to other tree species.

B. Field Measurement

In the study area, measurement of sample trees were conducted in February–March 2019. The measurement of sample trees aimed to obtain tree level data for formulating form factors and volume models and for assessing the accuracy of tree bole volume estimates. In the three villages, 150 sample trees were measured by considering tree diameter distribution to cover the variability of mahogany stands (Table 1). Non-defective sample trees with straight stems and fewer branches were selected to avoid measurement errors. The measurement of sample trees was conducted using non-destructive sampling (i.e. without cutting the sample trees). Diameter at breast height (D , cm) and base diameter at 20 cm above the ground

Table 1. Summary statistics of the sample trees measurement

Variable	Fitting data (n = 120)					Validation data (n = 30)				
	Mean	Sd	Min	Max	CV	Mean	Sd	Min	Max	CV
D_b	22.4	7.8	7	45	35	21.4	7.6	7	33	36
D	18.5	6.7	6	38	36	17.8	6.7	6	30	37
H_b	9.2	2.1	5	14	23	8.8	1.4	6	12	16
H_t	11.9	2.2	7	18	18	11.8	2.0	8	18	17

Remarks: D_b , base diameter (cm); D , diameter at breast height (cm); H_b , bole height (m); H_t , total height (m); Sd , standard deviation; CV , coefficient of variation (%)

(D_b , cm) were measured using a measuring tape. In addition, two types of tree height were also measured by using a Nikon laser hypsometer: bole height (H_b , m) and total height (H_t , m). The bole height (also called crown base height) was measured from the ground to the crown base of sample trees, in which the upper bole diameters were 3–19 cm with an average of 10 cm. Meanwhile, the total height was measured from the ground to the tip of canopy of sample trees. Husch et al. (2003) provided an illustration of the measurement points of bole height and total height, which were referred to in this study. Such height measurement of the sample trees was aimed to simulate possible errors in measuring tree heights for estimating the tree bole volumes of mahogany and to assess their accuracy.

To calculate the bole volume of a sample tree, diameters (over-bark) were measured at different heights (0.2, 1.2, 2.2 m and so on with 1 m sections) along the stem until the end of the bole height by using a Criterion RD 1000 digital dendrometer (Santos et al., 2019). Therefore, this study defined the actual tree volumes as tree bole volumes, which are also commonly used by communities in the study area. Total tree volume wasn't measured until the total height, because of difficulty in measuring all branches and the upper parts of the stem beyond the bole height. In further analysis, however, the total tree height was used as an input for the simple volume equations and volume models.

C. Analysis of Form Factors

There are 120 trees (80%) of the total 150 sample trees for calculating form factors and developing volume models, while the rest of the sample trees were used for independently validating tree bole volume estimates. Firstly, the individual volume of sample trees was calculated (V_p , m³) by adding sectional volumes of a stem, where each sectional volume (v_s , m³) was calculated based on basal areas at the lower (g_p , m²) and upper (g_u , m²) parts of each section and the length of each section (l_s , m) using the Smalian formula (Husch et al., 2003) as shown in Equation (1):

$$v_s = 0.5(g_l + g_u)l_s \dots\dots\dots (1)$$

The form factor (f , unitless) of individual sample trees was calculated as a ratio between the actual volume of a sample tree (V_p , m³) and the cylindrical volume of a sample tree at the same height (Husch et al., 2003; Philip, 1994). Two types of form factors were analyzed (Philip, 1994): 1) artificial form factor (f_d), where the cylindrical volume was calculated based on the basal area at breast height and the bole height of a sample tree (V_d , m³), and 2) absolute form factor (f_b), where the cylindrical volume was calculated based on the basal area at 20 cm above ground and the bole height of a sample tree (V_b , m³) using Equation (2a) and Equation (2b):

$$f_d = V_i/V_d \dots\dots\dots (2a)$$

$$f_b = V_i/V_b \dots\dots\dots (2b)$$

D. Development of Volume Models

There are 120 sample trees to develop volume models using a regression analysis. The tree bole volume (V , m^3) is used as a dependent variable, while the breast height (D , cm) and total height (H , m) are used as predictor variables. The use of total height in volume models provides a practical advantage for users, because it is easier and less subjective to measure than the bole height using linear and non-linear regression models that are commonly used in forestry literatures (Husch et al., 2003; Santos et al., 2019) as shown in Equation (3a) to Equation (3f):

$$VD1: V = b_0 D^{b_1} \dots\dots\dots (3a)$$

$$VD2: V = b_0 + b_1 D^2 \dots\dots\dots (3b)$$

$$VD3: V = b_0 + b_1 D + b_2 D^2 \dots\dots\dots (3c)$$

$$VDH1: V = b_0 D^{b_1} H_t \dots\dots\dots (3d)$$

$$VDH2: V = b_0 + b_1 D^2 H_t \dots\dots\dots (3e)$$

$$VDH3: V = b_0 D^{b_1} H_t^{b_2} \dots\dots\dots (3f)$$

To estimate the model parameters (b_0 , b_1 , and b_2), generalized linear and non-linear least square (GLS/GNLS) methods from the nlme package of R software 3.6.3 was used (Pinheiro, Bates, DebRoy, & Sarkar, 2020; R Core Team, 2020), which are more effective than the ordinary least square (OLS) methods in eliminating heteroscedasticity (non-constant variance) of the model residuals. The performance of regression models was assessed using the goodness-of-fit statistics: Root Mean Squared Error (RMSE; Equation (4a)), Akaike’s Information Criterion (AIC; Equation (4b)), and adjusted coefficient of determination (R^2_{adj} ; Equation (4c)) as follows (Burnham & Anderson, 2002; Cysneiros et al., 2020; Rawlings, Pantula, & Dickey, 1998):

$$RMSE = \sqrt{\sum_{i=1}^n (y_i - \hat{y}_i)^2 / (n - p)} \dots\dots\dots (4a)$$

$$AIC = -2 \log Lik + 2(p + 1) \dots\dots\dots (4b)$$

$$R^2_{adj} = 1 - \frac{(n - 1) \sum_{i=1}^n (y_i - \hat{y}_i)^2}{(n - p) \sum_{i=1}^n (y_i - \bar{y}_i)^2} \dots\dots\dots (4c)$$

Note that y_i, \hat{y}_i, \bar{y} are the observed, predicted, and mean values of tree bole volumes, respectively; n is the number of observations; p is the number of model parameters; and $\log Lik$ is the log-likelihood value of the models. The preferred volume models must have the lowest RMSE and AIC values but highest R^2_{adj} value and must satisfy the regression model's assumptions on normality and homoscedasticity of residuals. Two preferred models were selected: one that uses only the D as a predictor (Equation 3a to 3c) and another one that uses both D and H_t as predictors (Equation 3d to 3f) for further analyses.

E. Accuracy Assessment

To recommend form factors and volume models selected for estimating tree bole volumes of mahogany, it is validated by tree bole volume estimation derived from the simple volume equation, which used the artificial and absolute form factors (f_d and f_b), and from the selected volume models by using two methods: cross-validation and independent validation. In both validation methods, the following simple equation was used to calculate the bole volume of each sample tree (V , m^3) based on D , H , and f variables:

$$V_i = 0.25\pi (D_i / 100)^2 H_i f \dots\dots\dots (5)$$

Equation (5) shows that the accuracy of tree bole volume estimates is not only depending on the form factor (f_d or f_b) but also the height (H). Meanwhile, the diameter (D) could be assumed as a fixed variable because it is easy to measure with high accuracy in the field. Therefore, to assess the accuracy of simple volume equation (Equation 5) with respect to the use of f and H variables in estimating the actual bole volumes, it is simulated a scenario where users might not use an appropriate form factor and/or tree height by calculating the four types of simple volume equation as follows:

- 1) V_{fd-Hb} that uses the artificial form factor (f_d) and bole height (H_b).
- 2) V_{fd-Ht} that uses the artificial form factor (f_d) and total height (H).

- 3) V_{fb-Hb} that uses the absolute form factor (f_b) and bole height (H_b).
- 4) V_{fb-Ht} that uses the absolute form factor (f_b) and total height (H).

The prediction accuracy of the four simple volume equations and two selected volume models (among the Equation 3a to Equation 3f) was evaluated using the Monte Carlo cross-validation method (Huy et al., 2016; Kuhn & Johnson, 2013). The 120 sample trees were first randomly split into a fitting dataset (80%; 96 sample trees) and a validation dataset (20%; 24 sample trees). The four simple volume equations and two selected volume models were used to estimate tree bole volumes of the relevant dataset, and their prediction accuracy was then evaluated using the validation dataset. This process was repeated 200 times to get stable performance estimates (Kuhn & Johnson, 2013). For each realization (R), the prediction accuracy was assessed using Mean Error (ME; Equation (6a)), Percentage Error (PE; Equation (6b)), Root Mean Square Error of Prediction (RMSEP; Equation (6c)), and Mean Absolute Percentage Error (MAPE; Equation (6d)), which were then averaged over the 200 realizations (Huang, Yang, & Wang, 2003; Huy et al., 2016; Sileshi, 2014):

$$ME = \frac{1}{R} \sum_{r=1}^R \left(\sum_{i=1}^n (y_i - \hat{y}_i) / n \right) \dots\dots\dots (6a)$$

$$PE = \frac{1}{R} \sum_{r=1}^R \left(100ME / \left(\sum_{i=1}^n y_i / n \right) \right) \dots\dots\dots (6b)$$

$$RMSEP = \frac{1}{R} \sum_{r=1}^R \sqrt{\sum_{i=1}^n (y_i - \hat{y}_i)^2 / n} \dots\dots\dots (6c)$$

$$MAPE = \frac{1}{R} \sum_{r=1}^R \left((100/n) \sum_{i=1}^n |y_i - \hat{y}_i| / y_i \right) \dots\dots\dots (6d)$$

The prediction accuracy of tree bole volumes was high when the values of ME, PE, RMSE, and MAPE were low.

To further evaluate the prediction accuracy of the four simple volume equations and two selected volume models, the independent validation dataset of 30 sample trees (Table 1) were observed. This step aimed to emulate the application of simple volume equations and

volume models when used by communities to estimate tree bole volumes of mahogany in the field. Similar to the cross-validation step, each simple volume equation and volume model was used to predict the bole volumes of 30 sample trees. Their prediction accuracy was assessed by using the ME, PE, RMSEP, and MAPE calculated only for one realization.

III. RESULT AND DISCUSSION

A. Form Factors of Mahogany

The mean of artificial form factor (f_d) of mahogany trees was 0.68 with a standard deviation of 0.11, while that of absolute form factor (f_b) was 0.46 with a standard deviation of 0.09. The f_b was lower than f_d because the cylindrical volumes of fb used the base diameter greater than the breast height diameter of f_d . This finding is similar to Ardelina et al. (2015), who also found that the absolute form factor ($f_b = 0.55$) was lower than the artificial form factor ($f_d = 0.65$) of *Falcataria moluccana* species. The f_d of 0.68 is higher than that of reported by Wahjono and Soemarna (1987), who found the f_d of 0.46 for the mahogany trees of a plantation forest in East Java. This discrepancy could be attributed to some differences in determining the f_d . In this study, the mahogany trees whose small to medium diameters (6–38 cm) with lower bole heights (5–14 m) were selected that resulted in more cylindrical stems and higher f_d . Meanwhile, Wahjono and Soemarna (1987) used the mahogany whose medium to large diameters (25–59 cm) with higher bole heights (9–22 m) that resulted in more tapered stems with lower f_d .

Interestingly, the artificial and absolute form factors slightly decreased when the diameters at breast height increased (Figure 1). A similar trend was also reported by Tenzin et al. (2016), who observed that the form factors of nine commercial tree species in Bhutan were also gradually decreasing with increasing diameters. The diameters had very weak and not significant correlations with either the artificial form factor ($r = -0.18, P\text{-value} > 0.01$) or the absolute form

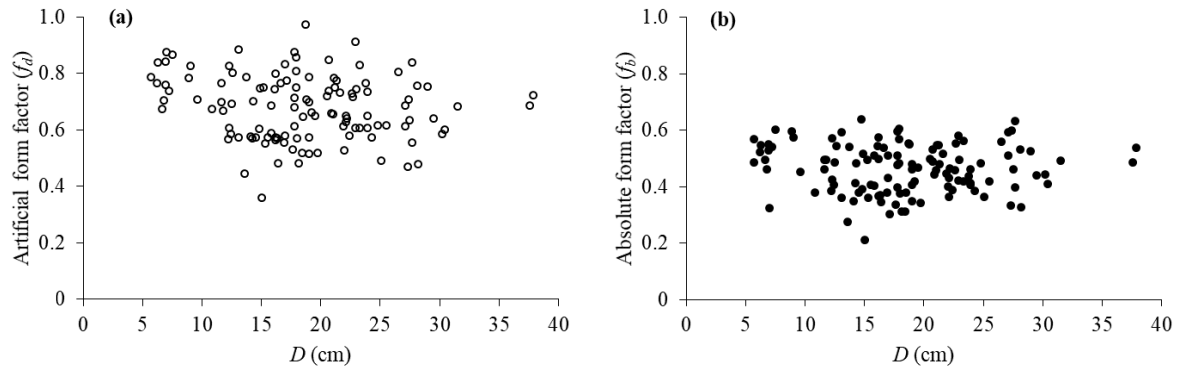


Figure 1. Relationship between diameter at breast height (D) and (a) artificial form factor (f_a) and (b) absolute form factor (f_b) of mahogany trees

Table 2. Parameter estimates and goodness-of-fit statistics of the volume models

Model	Parameter	SE	P-value	RMSE	AIC	R^2_{adj}	
VD1	b_0	0.00045	0.000052	0.0000	0.0400	-524.84	0.906
	b_1	2.02240	0.040313	0.0000			
VD2	b_0	-0.00111	0.001208	0.3613	0.0399	-525.68	0.907
	b_1	0.00049	0.000011	0.0000			
VD3	b_0	-0.00433	0.006138	0.4821	0.0396	-524.41	0.908
	b_1	0.00064	0.001207	0.5964			
	b_2	0.00047	0.000048	0.0000			
VDH1	b_0	0.00007	0.000009	0.0000	0.0333	-547.84	0.935
	b_1	1.80280	0.041948	0.0000			
VDH2	b_0	0.00645	0.001582	0.0001	0.0376	-544.46	0.917
	b_1	0.00004	0.000001	0.0000			
VDH3	b_0	0.00015	0.000029	0.0000	0.0330	-564.47	0.936
	b_1	1.88726	0.040492	0.0000			
	b_2	0.61614	0.087300	0.0000			

factor ($r = -0.05$, $P\text{-value} > 0.01$). Wahjono and Soemarna (1987) also observed a weak and not significant correlation ($r = 0.08$, $P\text{-value} > 0.01$) between the diameters and artificial form factor of mahogany. This finding suggested that the form factors were relatively constant; hence, it could estimate tree bole volumes of mahogany with diameters of 6–38 cm.

B. Volume Models for Mahogany

All of the volume models produced similar RMSE of 0.03–0.04 m³ and their independent variables (D and/or H) explained 91–94% of the total variation of tree bole volumes (Table 2). Among the three VD models, however, the VD2 and VD3 models had some parameters

(b_0 , b_1) that were not significant ($P\text{-value} > 0.01$), suggesting that these models were not appropriate for estimating the tree bole volumes. Thus, the VD1 provided a simple yet reliable model for estimating tree bole volumes of mahogany by only using D variable. The VD1 model produced residuals that approximately followed a normal distribution (Figure 2a), far better than those of the VD2 and VD3 models (not shown). The VD1 model also did not produce an obvious pattern of the residuals (Figure 2c), indicating that this model satisfied the assumption on homoscedasticity of residuals.

The addition of the H variable into volume models slightly improved the performance of

VDH models, in which the D and H variables were significant (P -value < 0.01) and explained 92–94% of the total variation of tree bole volumes (Table 2). This finding is consistent with Krisnawati et al. (2012), who reported that the addition of H other than D variables improved the performance of volume models by 3%. The VDH1 and VDH2 models were similar in terms of their goodness-of-fit statistics, meaning that there were no significant differences in the performance of these models. The VDH3 model, however, had better performance than the other VDH models because it produced the lowest AIC that differed by 17–20 compared to the AIC of VDH1 and VDH2 models. The AIC difference of > 10 indicated that the VDH3 model had a strong performance compared to the other models (Burnham & Anderson, 2002). Analysis of residuals also confirmed that the VDH3 model satisfied the assumption on normality and homoscedasticity of residuals (Figure 2b and 2d). Thus, the VDH3 (also called the Schumacher-Hall model in forestry literature)

was the most reliable model for estimating tree bole volumes of mahogany, especially when the D and H data were available. The reliability of Schumacher-Hall model (VDH3) was also reported by Cysneiros et al. (2020) who developed tree volume models for the main forest types of the Atlantic Forest region.

C. Accuracy of the Volume Estimates

When the artificial and absolute form factors were used to estimate tree bole volumes using the simple volume equations, their accuracy was affected by the tree heights (Table 3). The artificial form factor (f_d) generated the most accurate estimate of tree bole volumes (PE -3.8 and 0.2%) when it was used with the bole height (H_b) in the $V_{f_d H_b}$ model. The highest accuracy of the $V_{f_d H_b}$ model was also indicated by the lowest values of ME, RMSEP, and MAPE compared to the other simple volume equations. However, the f_d generated a higher negative bias (PE -38%), meaning that its tree bole volume estimates were higher than the actual tree bole volumes when it was used with the total height

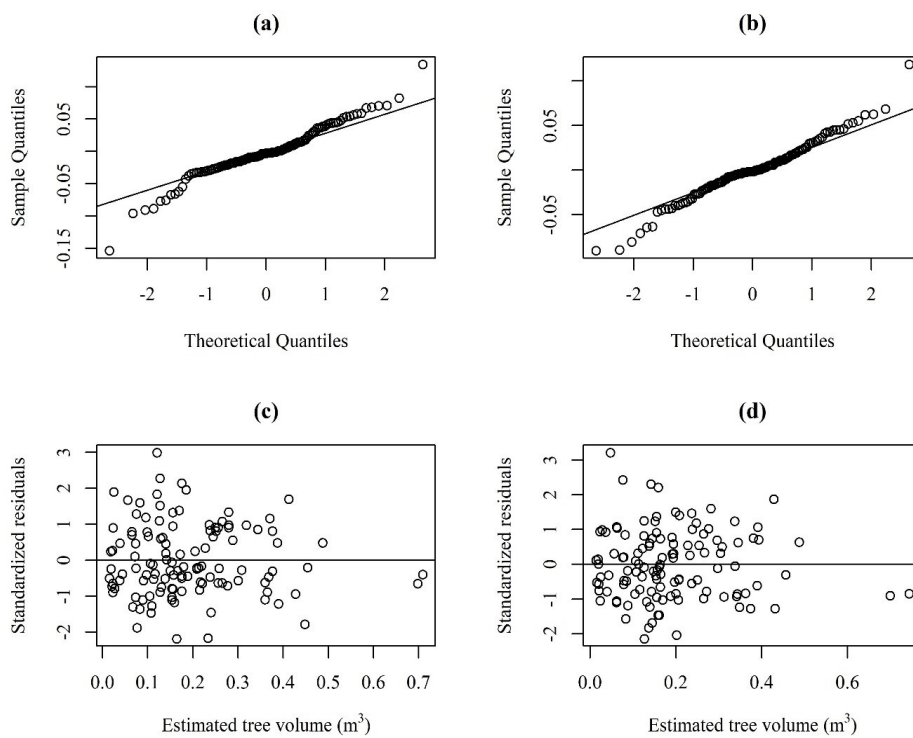


Figure 2. The normal probability plot of the residuals of (a) VDH1 and (b) VDH3 models and the distribution of standardized residuals of (c) VDH1 and (d) VDH3 models

Table 3. Accuracy statistics of the four simple volume equations and two selected volume models

Model	Validation	ME (m ³)	PE (%)	RMSEP (m ³)	MAPE (%)
V _{fd-Hb}	Cross	-0.0067	-3.8	0.035	15.9
	Independent	0.0003	0.2	0.024	11.7
V _{fd-Ht}	Cross	-0.0707	-37.9	0.103	35.5
	Independent	-0.0652	-37.6	0.100	35.7
V _{fb-Hb}	Cross	0.0545	29.6	0.071	30.9
	Independent	0.0563	32.5	0.071	32.4
V _{fb-Ht}	Cross	0.0119	6.5	0.036	15.9
	Independent	0.0120	6.9	0.042	16.4
VD1	Cross	-0.0013	-0.7	0.040	16.3
	Independent	-0.0003	-0.2	0.038	15.8
VDH3	Cross	-0.0012	-0.7	0.034	13.5
	Independent	-0.0067	-3.9	0.037	14.2

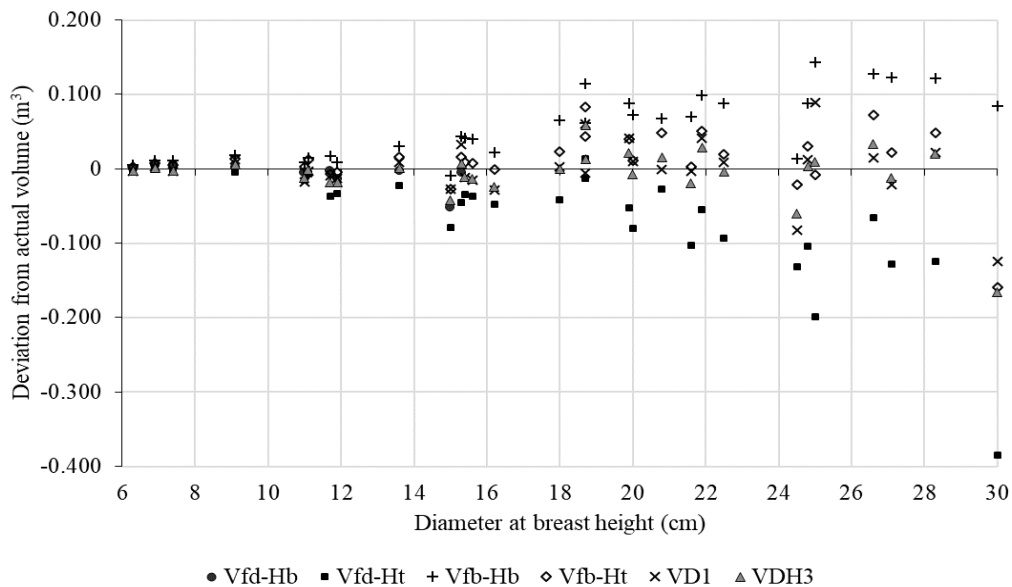


Figure 3. The deviation of tree bole volume estimates generated by the simple volume equations and volume models using the independent validation dataset

(H_b) in the V_{fd-Ht} model. In contrast, the absolute form factor (f_b) generated a high accuracy of tree bole volume estimates (PE 7%) when it was used with the H_t in the V_{fb-Ht} model, but it generated a low accuracy of tree bole volume estimates (PE 30% and 33%) when it was used with the H_b in the V_{fb-Hb} model. Compared to the other simple volume equations, the V_{fd-Hb} and V_{fb-Ht} models produced smaller deviations of tree bole volume estimates (Figure 3). These findings suggested that one must use either the

artificial form factor ($f_d = 0.68$) coupled with the bole height (V_{fd-Hb} model) or the absolute form factor ($f_b = 0.46$) coupled with the total height (V_{fb-Ht} model) to obtain high accuracy in estimating tree bole volumes of mahogany using the simple volume equation.

As expected, the selected volume models (VD1 and VDH3) generally produced more accurate tree bole volume estimates than the simple volume equations (Table 3). The deviations of tree bole volume estimates

generated by the VD1 and VDH3 models were also smaller than those of the simple volume equations (Figure 3). The MAPE of VDH3 model was lower than that of the VD1 model, confirming that the VDH3 model was more accurate than the VD1 model. In the absence of tree height data, however, the VD1 model could also be used to estimate the tree bole volumes because its MAPE was only marginally lower (1.6–2.8%) than that of the VDH3 model but their RMSEP values were similar.

D. Options for Estimating Tree Bole Volumes

This study revealed that communities could use the V_{fd-Hb} , VDH3, or VD1 model to estimate tree bole volumes of mahogany in the study area. The V_{fd-Hb} and VD1 have similar accuracy, while the VDH3 has the highest accuracy. These models are reliable to use because they provide acceptable accuracy (PE < 5%, RMSEP < 0.05 m³, and MAPE < 16%). Communities may choose one of them by considering availability of input data and anticipating possible errors when applying those models. All models confirmed that bias increased when diameter increased (Figure 3), suggesting that communities should measure more carefully larger trees than smaller trees.

The V_{fd-Hb} uses a simple volume equation that involves diameter, bole height, and form factor (Equation (5)). This simple volume equation is commonly used in practice when a volume model is not available. Because such a volume equation is not a regression model, it is also commonly used without considering the range of diameter and height data. This practise should be avoided when using the volume model, because prediction biases would occur when a volume model is used outside the range of the diameter and height data. The lack of information on form factors often motivates users to use a general artificial form factor of 0.6 (Krisnawati et al., 2012). However, the results of this study warn users to selectively use an appropriate form factor and tree height when using the simple volume equation. The V_{fd-Hb}

confirmed that the artificial form factor of 0.68 must be used with the bole height data to get accurate tree bole volume estimates. The bole height, however, might not be easy to measure in the field because it might be confusing when determining the crown base of trees. In practice, it is easier to measure the total height rather than the bole height, because the tip of canopy is easy to observe when measuring the total height of mahogany trees that commonly grow sparsely in community forests. But, this study confirmed that the use of total height coupled with the artificial form factor produced a high negative bias, meaning that the simple volume equation (V_{fd-Ht}) generated higher tree bole volume estimates than the actual tree bole volumes. To reduce the bias, communities should use the total height coupled with the absolute form factor of 0.46 (V_{fb-Ht}) instead of the artificial form factor when they use a simple volume equation. The use of an appropriate form factor is also recommended by Henry et al. (2010), who observed a significant bias in converting tree volume into tree biomass when the simple volume equation was used with a general form factor of 0.6.

While the simple volume equation (V_{fd-Hb} or V_{fb-Ht}) requires a careful choice of form factor and height data, the volume models (either VDH3 or VD1) provide a clear choice of input data. The VDH3 model uses both the diameter at breast height and total height, which is easier to measure than the bole height. While the diameter is easy to measure by using a measuring tape, the total height is not easy to measure in the field (Husch et al., 2003; Larjavaara & Muller-Landau, 2013; Magnussen et al., 2020) without using a hypsometer that might not be available in the communities. However, in this emerging technology era, communities can use a smartphone-based application for measuring tree height with acceptable accuracy (Vastaranta et al., 2015). When communities are grouped in a forest owner's association, they could purchase or rent a hypsometer device, either a mechanical hypsometer (e.g. Haga altimeter) or a laser rangefinder (Larjavaara & Muller-

Landau, 2013), for supporting the management of community forests. In addition, it is also necessary to assist communities on how to use measurement devices for estimating tree bole volumes by using the volume model. This could be a task of forestry extension officers to educate community forest owners.

The simplest way for estimating tree bole volumes of mahogany is using the VD1 model. Compared to the V_{fd-Hb} and VDH3, the VD1 model provides a practical advantage for communities because it only requires tree diameter data that are easy to measure in the field (Santos et al., 2019). Most of the variability (91%) of tree bole volumes is accounted for by diameter in the VD1 model, suggesting that diameter alone is sufficient for estimating tree bole volumes. Santos et al. (2019) also found that a volume model using only diameter provided accurate volume estimates of african mahogany (*Khaya ivorensis*) trees. However, communities should be aware that the VD1 model only applies to the current mahogany stands whose total tree heights were relatively uniform throughout the study area (CV of 17–18%, Table 1). It is not surprising therefore, that the additionality of total height in the VDH3 model only explains 3% of the variability of tree bole volumes (Table 2). For practical purposes, the VD1 model could also be used for estimating the tree bole volumes of mahogany in other community forest areas with relatively homogeneous total tree heights.

IV. CONCLUSION

The mahogany trees at the study area had an artificial form factor of 0.68 ± 0.11 and an absolute form factor of 0.46 ± 0.09 . These form factors could be used in a simple volume equation, but their accuracy depended on tree height data. The simple volume equation using the artificial form factor and bole height data provided accurate estimates of the tree bole volumes. In a simple volume equation, total height should not be used with the artificial form factor, but it could be used with the

absolute form factor. The most accurate way to estimate the tree bole volumes of mahogany was using the volume model that uses diameter and total height (VDH3). When total height data were not available, the most practical yet reliable way to estimate the tree bole volumes was using the volume model that only uses diameter (VD1). This volume model is useful for supporting community forest management in the study area.

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