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USING 3D SCANNING TECHNIQUE FOR ESTIMATING FOREST STANDING VOLUME

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Abstract. The use of 3D (three-dimensional) scanning in calculating tree's volume is discussed and suitable equations are fitted for estimating stand volume based on stem diameter at breast height (DBH) and height in the form of power and logarithmic functions. One hundred eighty-four individuals of *Hopea odorata*, *Dipterocarpus alatus* and *Afzelia xylocarpa* were scanned. Then, 3D images were used to calculate an individual tree's volume, based on sectioning the main stem and branches by assuming the cylinder of each section. The results indicated that 3D image calculations underestimated volume by 2.1-4.8% compared to the water displacement method by testing spiral branches of 4.3-15.7 cm diameter. The logarithmic function is the best-fitted model for each species and the combination of three species. *A. alatus*, *H. odorata* and combination of three species require both DBH and height, while *A. xylocarpa* needs only DBH in volume estimation. All four best fitted equations have Adjusted R-Squared >0.88 and underestimate <0.9% 3D volume. The smallest underestimate of 0.02% 3D volume belongs to the best-fitted equation for combination of three species, indicating the potentiality of using a combination of three species equation for estimating the volume of all species, especially in natural forests. It is concluded the suitability of using the 3D scanning technique for calculating individual tree's volume with high accuracy and establishing volume equations for multiple species applications, especially in the tropical forest.

Keywords: cylinder form; individual volume calculation; sectioning; tropical forest; underestimate.

1 Introduction

A tree has a cylinder growth form, therefore cylinder form factor is used in tree volume estimation (Grosenbaugh, 1966; Hoyer and Gerald, 1985). If the cylinder form factor could be determined accurately for standing trees, an estimate of tree volume could be obtained without references to the volume equation. However, the measurement of cylinder form factor in the field is a difficult task. In addition, the cylinder form factor for a species changes by stand ages, growth conditions and many other surrounding factors, leading to failure to estimate the volume in a specific stand (Hazard and Berger, 1972). Therefore, foresters usually avoid the direct use of cylinder form factor in favor of volume equations that require stem diameter at breast height (DBH) or both DBH and height. Stem volume is a function of a tree's height and DBH (Altherr, 1960; Assmann, 1970; Heger, 1965). Tree height and DBH are easily measured. Therefore, the volume of any tree is easily estimated (Roebbelen and Smith, 1981), if equations are available.

Destructive sampling of sampled trees has been widely used for establishing allometry (Bao et al., 2016; Brown, 1997) and tree volume equations (Roebbelen and Smith, 1981). However, destructive sampling wastes resources and damages the environment, is complicated, heavy-work loaded (Yang and Harold, 2019), needs cutting many trees and sometimes is inapplicable where cutting sampled trees is not allowed such as natural and/or persevered forests. Destructive sampling has not become a preferred method recently (Abramo et al., 2007; He et al., 2016). The 3D (three dimensional) scanning technique has been widely used in many applications such as construction, mechanical structures and mining (Fan, 2004; Zhao and Hu, 2010), but it is still limited to forestry applications (Deng et al., 2005; Erik et al., 2004; Wu et al., 2008). 3D scanning technique doesn't

Table 1: Summary of the scanned trees and their parameters following species and planting year.

Species	Parameters	Planting year											
		1985	1991	1993	1995	1996	1997	2001	2005	2009	2010	2011	2012
D. alatus	Tree number	15	7						13	19			9
	DBH max (m)	0.43	0.39						0.38	0.31			0.21
	DBH min (m)	0.25	0.18						0.11	0.15			0.13
	H max (m)	25.97	18.77						27.77	18.97			14.70
	H min (m)	15.77	15.52						13.50	8.40			8.56
A. xylocarpa	Tree number		15			17							
	DBH max (m)		0.55			0.35							
	DBH min (m)		0.19			0.15							
	H max (m)		24.75			15.17							
	H min (m)		6.19			9.22							
H. odorata	Tree number		7	9	11		11	12	8		9	16	6
	DBH max (m)		0.45	0.42	0.34		0.40	0.35	0.22		0.16	0.21	0.21
	DBH min (m)		0.32	0.26	0.20		0.22	0.14	0.18		0.10	0.09	0.13
	H max (m)		20.59	21.11	18.23		24.71	22.83	13.83		8.82	15.06	9.55
	H min (m)		17.86	14.10	11.53		15.16	8.42	7.02		5.42	5.78	5.81

Note: cells without data mean data unavailable. There were no plantations established in such years.

destruct and causes no harm to scanned object (Cao et al., 2015; Nguyen et al., 2016). Therefore, 3D scanning technique seems to be useful in forestry applications, because it allows sampled trees to be alive and continue growing (Lindberg and Johan, 2017). Wu et al. (2008) applied 3D scanning technique to measure tree height and diameter with high precision compared to traditional method of destructive sampling. Hypypa (2001) used 3D scanning technique in forestry research and indicated that the standard errors were 9.9%, 10.2% and 10.5% for mean height, basal area and stem volume estimation, respectively.

Vietnam has a total natural forest area of 10.2 million ha. Of which, 4 million ha is production forest with high diversity of commercially valuable timber species. Therefore, estimating standing volume of such species play an important role for logging activity. The objectives of this study were to identify an individual tree's volume by using the 3D scanning technique and to establish suitable equations for estimating the stand volume of commercially valuable timber species of *Hopea odorata*, *Dipterocarpus alatus* and *Afzelia xylocarpa*.

2 Material and method

2.1 Area and Species

The study site locates in southern Vietnam, at Dong Nai Biosphere Reserve. Details of the study site can be found in work conducted by Nguyen et al. (2022). Plantations of three commercially valuable timber species of *H. odorata*, *D. alatus* and *A. xylocarpa* were established during 1985-2012 (Table 1). In these plantations, 184 individual trees were selected and scanned for 3D images.

2.2 Field Scanning and Volume Calculation

3D scanner (ZEB Go brand) and corresponding software (https://geoslam.com/) were used in this study. A person held a 3D scanner and walked around sampling trees to scan. The scanning process ensured that the main stem, all branches and crown were observed, scanned and recorded in 3D images (Fig. 1a). Each tree

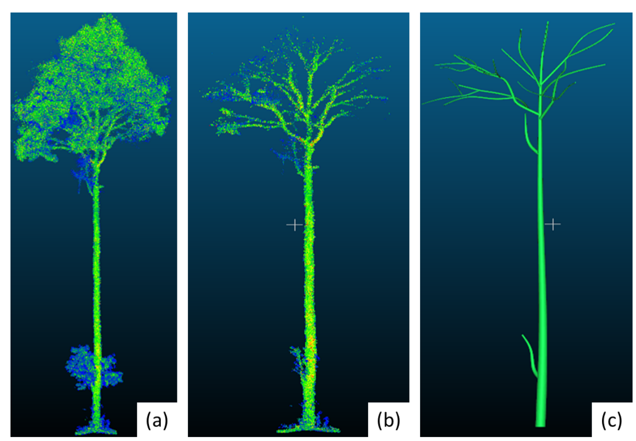

Figure 1: Steps for analyzing 3D image: whole scanned tree (a), point cloud tree (b) and mesh tree (c).

was scanned three times from different angles, height positions and distances from stem to a scanner (Mao and Wang, 2005; Zheng et al., 2005). After walking around a sample tree and scanning, a 3D image was automatically generated and recorded as a file, which was ready to download to a computer for the analyzing steps.

We used tools in www.3dsystems.com 3D analyzing software to analyze our 3D images (Fig. 1a)

(Zheng, 2005). Firstly, available tools were use to remove all leaves to achieve the point cloud tree (Fig. 1b). Secondly, the point cloud tree was smoothed to achieve the mesh tree (Fig. 1c). Thirdly, the mesh tree was sectioned into three groups as the main stem (trunk), branches with diameter $\geq$ 5 cm and branches with diameter 5 cm, each section had length of 0.1–0.8 m. Fourthly, volume of each section was calculated separately with the assumption of a cylinder of each section. Finally, volumes of all sections were summed up for whole tree's volume, called 3D volume (Wu et al., 2008). Volumes of three 3D images of each scanned tree (Fig. 1a) were calculated separately and their mean volume was used for further analyzes.

2.3 Regression Model

Stem DBH and height (H) are easily measurable parameters, which have been related to stem volume (V) through a variety of models in the forms of power and logarithm (Hoyer, 1985). Stem volume is estimated by the following equations:

$$V = a + b \times DBH^2 \times H \quad (1)$$

$$\log_{10}(V) = a + b \times \log_{10}(DBH^2 \times H) \quad (2)$$

$$\log_{10}(V) = a + b \times \log_{10}(DBH) \quad (3)$$

$$\log_{10}(V) = a + b \times \log_{10}(H) \quad (4)$$

where: in equations (1), (2), (3) and (4), a and b are constant; models were fitted to data and the best ones were selected by evaluation of Adjusted R-Squared (R^2); the significance of parameters, and the Akaike Information Criterion (AIC, calculated in Eq. (5)), calculated as follows:

$$AIC = -2\ln(L_h) + 2p \quad (5)$$

where: L_h is the likelihood of the fitted model; and p is the total number of parameters in the model.

The residual standard error (RSE) was also reported in the best model evaluation, deviation (De; %) of the estimate ($V_{estimate}$) versus 3D total volume (V_{3D}) was used: $De = 100 \times (V_{estimate} - V_{3D})/V_{3D}$.

The values of AIC, R^2, RSE and De were calculated for each model in equations (1), (2), (3) and (4). In each species and combination of three species, the model with lowest value of AIC, highest value of R^2 and lowest value of the significance of parameters was selected as the best model. RSE and De were used to additionally report significance of the best model.

3 Results

There were 63 individuals of *D. alatus* scanned, which were 36, 30, 19, 12 and 9 years old. The number was 32 individuals for *A. xylocarpa,* which were 30 and 25 years old and 89 individuals for *H. odorata*, which were 30, 28, 26, 24, 20, 16, 11, 10 and 9 years old. The 3D volume ranged from 0.027 to 1.423 $m^3/tree$ for *H. odorata*, 0.124–2.052 $m^3/tree$ for *A. xylocarpa* and 0.060–1.73 $m^3/tree$ for *D. alatus.*

Four models for estimating an individual tree's volume were fitted and statistical parameters for fitted models are listed in Table 2. All three species have very low significant values ($\leq$ 0.001) for *the b coefficient.* While among three species *H. odorata* has the smallest AIC (from -178.95 to -47.19) and RSE (from 0.09 to 0.18) and the largest R^2 (from 0.84 to 0.96). Meanwhile, *A. xylocarpa* has the largest AIC (from -47.96 to 9.53) and RSE (from 0.10 to 0.26) and smallest R^2 (from 0.26 to 0.88). For combination of three species, fitted models have the lowest AIC (from -5.26 to -287.59) and the second-lowest R^2 (from 0.68 to 0.93) and RSE (from 0.10 to 0.23), only following that of *A. xylocarpa* (Table 2). Fourteen of 16 deviation values (De) are negative indicating underestimation of an individual tree's volume using such equations.

The best fitted model for *D. alatus* is $\log_{10}(V) = -0.417 + 0.897 \times \log_{10}(DBH^2 \times H)$ with underestimation of 0.86% volume, *H. odorata* is $\log_{10}(V) = -0.359 + 0.885 \times \log_{10}(DBH^2 \times H)$ with underestimation of 0.36% volume and *A. xylocarpa* is $\log_{10}(V) = 0.815 + 2.078 \times \log_{10}(DBH)$ with underestimation of 0.33% volume. While the best fitted model for combination of three species is $\log_{10}(V) = -0.379 + 0.876 \times \log_{10}(DBH^2 \times H)$, which underestimates 0.02% volume.

The deviation between best fitted and least fitted models is shown in Figures 2–5. There are significant divergences between 3D volume and least fitted (Fig. 2b, 3b, 4b and 5b) compared to that between 3D volume and best fitted (Fig. 2a, 3a, 4a and 5a) in all three species. In best fitted, there are smooth data points of all best-fitted ones, while they are quite noise among data points of all least-fitted ones.

4 Discussion

To accurately calculate the volume of sampled trees, scanning for 3D images and analyzing them (Zheng et al., 2005) for volume are important keys. In plantations and more difficultly in natural forests, it is not easy to observe the whole canopy of a tree, since canopies of surrounding trees are overlapping and are crossing each other, therefore capturing images of the whole stem and all sized branches becomes a difficult task (Liyan et al., 2018). Any invisible branches and top part of the trunk, which are not observed and recorded in 3D image, will lead to under-calculation of the tree's 3D volume. To minimize under-calculation (Berger et al., 2014), in the present study each tree was scanned three times and

Table 2: Equations for estimating the standing volume (V, m^3) of an individual tree.

Species	Equation	b (sig.)	AIC	R2	RSE	De (%)
D. alatus	V = 0.085 + 0.311 × DBH2 × H	0.000	-28.50	0.81	0.17	19.12
	Log10(V) = -0.417 + 0.897 × Log10(DBH2 × H)	0.000	-66.72	0.88	0.12	-0.86
	Log10(V) = 1.013 + 2.356 × Log10(DBH)	0.000	-32.25	0.80	0.18	2.73
	Log10(V) = -3.434 + 2.483 × Log10(H)	0.000	-18.80	0.75	0.19	-0.87
A. xylocarpa	V = 0.123 + 0.345 × DBH2 × H	0.000	0.28	0.73	0.23	-2.76
	Log10(V) = -0.335 + 0.828 × Log10(DBH2 × H)	0.000	-38.86	0.84	0.12	-3.50
	Log10(V) = 0.815 + 2.078 × Log10(DBH)	0.000	-47.96	0.88	0.10	-0.33
	Log10(V) = -2.212 + 1.707 × Log10(H)	0.001	9.53	0.26	0.26	-2.44
H. odorata	V = 0.050 + 0.373 × DBH2 × H	0.000	-166.46	0.94	0,09	-1.48
	Log10(V) = -0.359 + 0.885 × Log10(DBH2 × H)	0.000	-178.95	0.96	0.08	-0.36
	Log10(V) = 1.227 + 2.717 × Log10(DBH)	0.000	-128.73	0.93	0.11	-1.23
	Log10(V) = -2.869 + 2.124 × Log10(H)	0.000	-47.19	0.84	0.18	-7.13
Three species	V = 0.072 + 0.342 × DBH2 × H	0.000	-179.46	0.87	0.14	-2.19
	Log10(V) = -0.379 + 0.876 × Log10(DBH2 × H)	0.000	-287.59	0.93	0.10	-0.02
	Log10(V) = 1.084 + 2.506 × Log10(DBH)	0.000	-221.51	0.90	0.13	-2.39
	Log10(V) = -2.762 + 2.017 × Log10(H)	0.000	-5.26	0.68	0.23	-10.98

mean 3D volume was used for establishing the volume equation (Table 2).

Trunk and branches generally have cylinder forms (Fig. 1). However, in some specific cases, trees have prominent buttresses and spiral main stems and branches. Like other techniques, this makes volume calculation from 3D images more difficult and less accurate (He et al., 2016; Yang and Harold, 2019). Therefore, trees with prominent buttresses and spiral main stems and branches should not be selected as sampled trees for scanning 3D images. Water displacement method was used to test the accuracy of 3D image volume calculation. To use this method, several spiral branches of 4.3–15.7 cm diameter were inserted into a graduated cylinder partially filled with water. The volume of spiral branch occupied space, displacing water and raising the water level. The results indicated that 3D image calculations underestimated 2.1–4.8% volume compared to water displacement method. While similar tests for cylinder branches indicated an underestimate 0.3–1.4% volume by 3D images compared to the water displacement method. 3D image volume calculation underes-

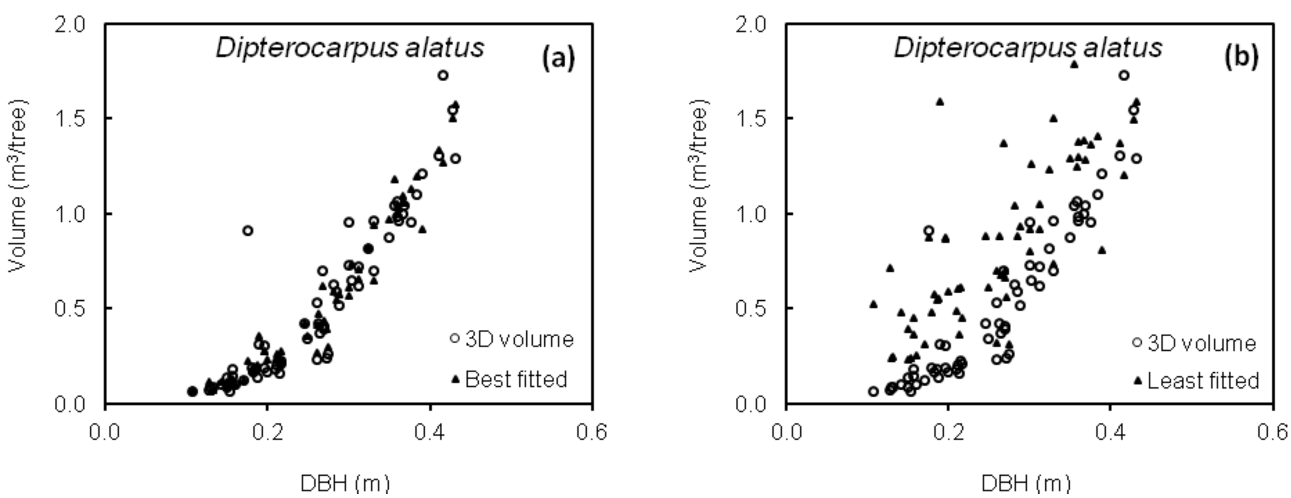

Figure 2: Comparing 3D volume and best-fitted model (a) and least-fitted model (b) for *Dipterocarpus alatus*.

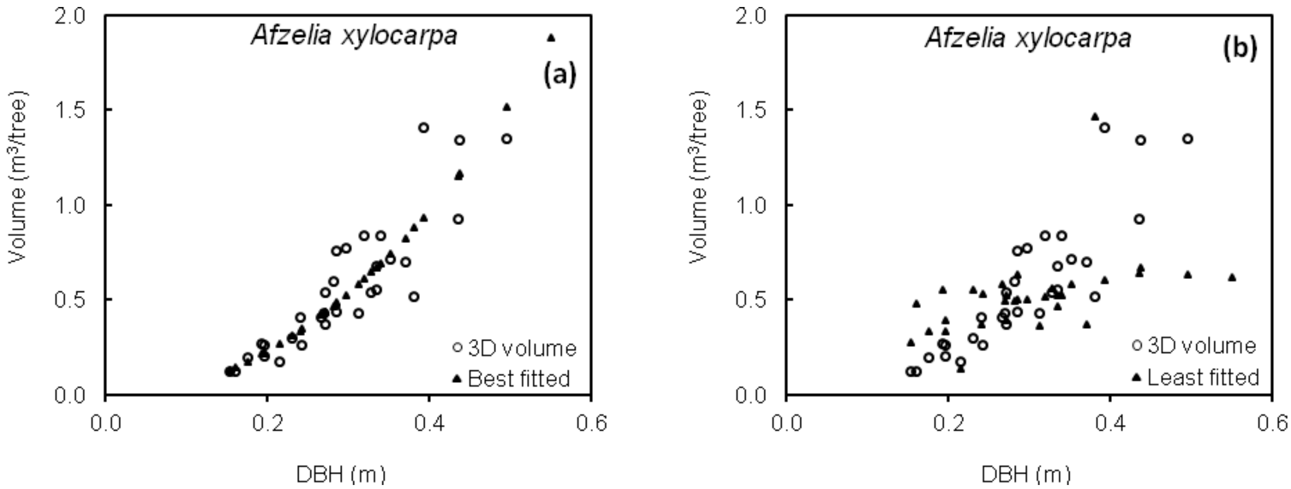

Figure 3: Comparing 3D volume and best-fitted model (a) and least-fitted model (b) for *Afzelia xylocarpa*.

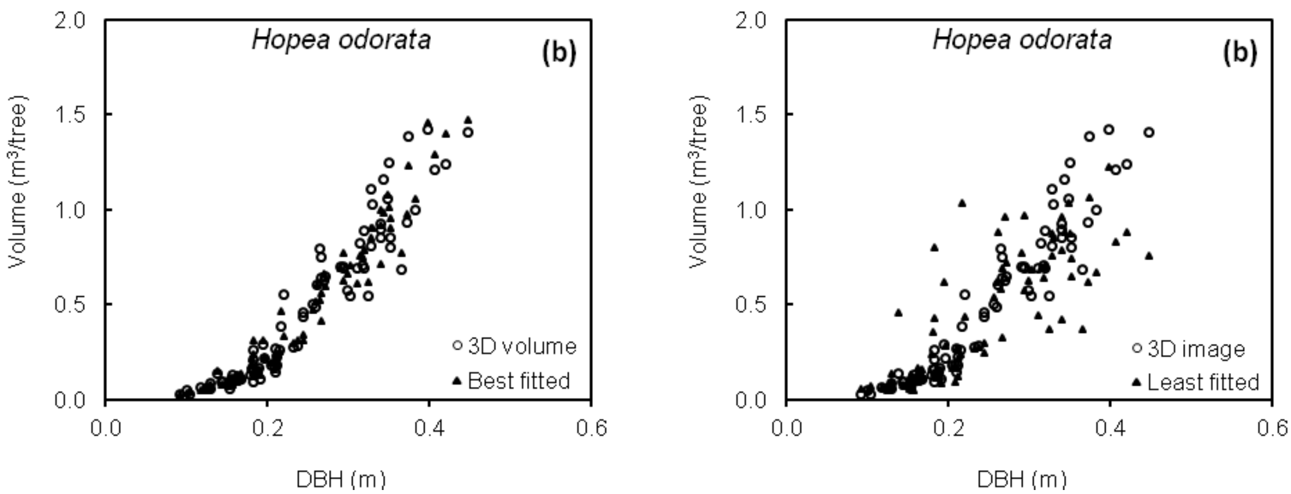

Figure 4: Comparing 3D volume and best-fitted model (a) and least-fitted model (b) for *Hopea odorata*.

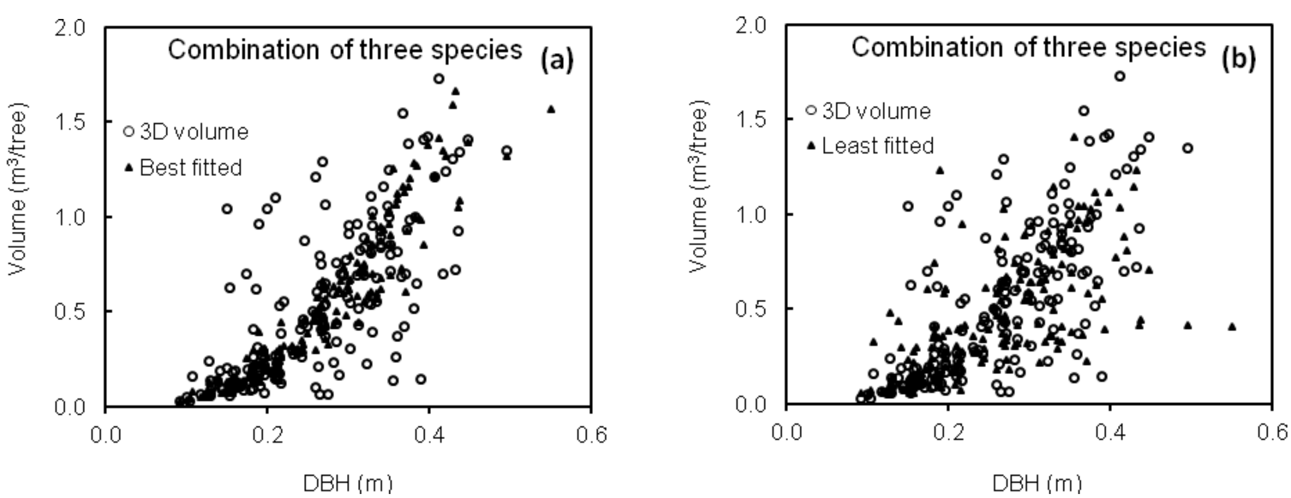

Figure 5: Comparing 3D volume and best-fitted model (a) and least-fitted model (b) for combination of three species.

timates the real one and the best-fitted equations (Table 2) also underestimate the 3D image calculated volume, both lead to a slight underestimation of an individual tree's volume by using the best-fitted equations.

Cylinder form factor (f) has been widely used in estimating an individual tree's volume in the form of $V = G \times H \times f$ (Silva et al., 1994), where G is the basal area. Equation (1) in this study has a similar form. However, it is not the best-fitted model for each species and combination of three species (Table 2). It is well known that the cylinder form factor varies from stand to stand and tree to tree within a stand. It is easily applicable for foresters but results in less accurate volume estimation. In the present study for each species and combination of three species (Table 2), equation (1) is much underestimated (2.2-19.1%) compared to best-fitted equations of the logarithmic form (<0.9%) and errors in other methods (Hypypa, 2001; Straub and Koch, 2011; Tompalski et al., 2014; Vonderach and Voegtle, 2012).

The logarithm is the best-fitted model for each species and combination of three species. However, *A. alatus*, *H. odorata* and combination of three species require both DBH and height, while *A. xylocarpa* needs only DBH (Table 2). This makes volume estimate for *A. xylocarpa* much easier since DBH measurement is much easier and more accurate compared to measuring a tree's height. However, knowledge of cylinder tree stem indicated the necessity of both DBH and height in accurate volume estimation (Altherr, 1960; Assmann, 1970; Grosenbaugh, 1966). The result of the best-fitted equation in this study for *A. xylocarpa* ($Log_{10}(V) = 0.815 + 2.078 \times \log_{10}(DBH)$) may come from the fact of a small number of only 32 sampled trees in two ages of 25 and 35 years old, compared to 63 trees of *A. alatus* in five ages of 36, 30, 16, 12 and 9; and to 89 trees of *H. odorata* in nine ages of 30, 28, 26, 24, 20, 16, 11, 10 and 9 years old. This is confirmed by the best-fitted model for combination of three species ($\log_{10}(V) = -0.379 + 0.876 \times \log_{10}(DBH^2 \times H)$) with 184 sampled trees, resulting in an underestimated 0.02%, the smallest one among all fitted equations (Table 2). The visualization of underestimates among four best-fitted models is shown in figures 2a, 3a, 4a and 5a, indicating divergences between 3D volumes and the best-fitted ones.

Altherr (1960) and Assmann (1970) identified an approximate 4% underestimate of tree volume as calculated by Hohenadl's method, by using diameter measured at proportional distances along the tree bole. While in the present study measuring DBH and stem height is enough for accurate estimation (Table 2) and all four best-fitted equations have underestimated less than 0.9 %, especially for combination of three species which underestimates only 0.02 %. This suggested that if a species-specific volume equation is not available, the equation for combination of three species could also be applicable with high accuracy. Therefore, to establish a volume equation for natural forests, especially natural tropical forests which may contain more than 100 species per hectare, scanning 3D images of several dominant species is good enough. In addition, tree forms are changing stand by stand, age by age, size by size and others (Hazard and Berger, 1972). Such points should be carefully considered when selecting sampled trees for scanning, especially for natural forests; scanned trees should be distributed in different sizes, positions in a stand and positions in the canopy (e.g. upper canopy, middle canopy and low canopy) to cover as many cylinder growth forms as possible.

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