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The Importance of Tree Height in Estimating Individual Tree Biomass while Considering Errors in Measurements and Allometric Models

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ABSTRACT

This study evaluated the uncertainty of individual tree biomass estimated by allometric models by both including and excluding tree height independently. Using two independent sets of measurements on the same trees, the errors in the measurement of diameter at breast height and tree height were quantified, and the uncertainty of individual tree biomass estimation caused by errors in measurement was calculated. For both allometric models, the uncertainties of the individual tree biomass estimation caused by the use of a specific allometric model were also calculated. Finally, the overall uncertainty of individual tree biomass by combining the two uncertainties was calculated. The allometric model including tree height was 6 % more accurate than that excluding tree height when the uncertainty caused by allometric models became the only consideration. However, in terms of the uncertainty caused by measurement, the allometric model excluding tree height was three times more accurate than allometric model including tree height. As a result, the allometric model excluding tree height was 5 % more accurate than the allometric model including tree height when both causes of uncertainty, the allometric model and measurement errors were considered. In conclusion, errors in tree height measurement have the potential to increase the error of aboveground biomass estimation.

INTRODUCTION

Human activities cause drastic deforestation and forest degradation in many tropical forests (Laurance, 2007). As a result, the carbon emissions derived from deforestation and forest degradation are important factors in the global carbon budget (Canadell et al., 2007). Reducing emissions from deforestation and forest degradation, improving the role of conservation and sustainable management of forests, and enhancement of forest carbon stocks in developing countries (REDD+) is one example of a framework for enhancing and conserving carbon stocks of forested areas in the tropics. Conceptually, REDD+ creates financial incentives designed to encourage developing countries to manage forests sustainably, improve their forest management techniques and to protect their forest resources; this is done by recognizing the financial value of carbon stored in forests (Corbera & Schroeder, 2011).

Effective implementation of REDD+ activities requires scientifically robust estimates of the carbon emissions (Böttcher et al., 2009). For the Estimation of carbon emissions, it is required to quantify the spatial extent of deforestation and forest degradation, and the amount of carbon that was stored in those forests (Gibbs, Brown, Niles, & Foley, 2007). In many cases, forest carbon stocks are calculated from aboveground biomass (AGB) of the forest by assuming a carbon content 50 %.

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Individual tree biomass is the underlying basis of the estimation of forest level AGB (e.g. Gibbs, Brown, Niles, & Foley, 2007; Englhart, Jubanski, & Siegert, 2013). Hence, if individual tree biomass is unknown or uncertain, this affects the robustness of estimates of emissions and such estimates should be quantified to provide a sound and scientific background for REDD+ programs.

Individual tree biomass is typically estimated by substituting measured tree parameters (e.g. DBH – diameter at breast height) into an allometric model. Because both tree measurements and allometric models are subject to errors, estimates of individual tree biomass contain uncertainty caused by errors in measurements, and by deficiencies in allometric models. Both of these types of errors must be evaluated to accurately estimate tree biomass.

Many studies have evaluated errors created during in the assessment and physical measurements of trees (e.g. Elzinga, C., Shearer, & Elzinga, G., 2005; Kitahara, Mizoue, & Yoshida, 2008). However, the studies focusing on the effect of these errors on the estimation of individual tree biomass are considerably few (Berger, Gschwantner, McRoberts, & Schadauer, 2014). Berger, Gschwantner, McRoberts, & Schadauer (2014) assessed the effects of errors in measurements on estimating individual tree volume using Austrian national forest inventory data. Mason et al. (2014) also assessed the effects of measurement errors on carbon storage estimates in shrubland. Only limited research has focused on errors created during tree measurement in tropical forests. Hunter, Keller, Victoria, & Morton (2013) reported that errors in tree height measurement led to 5–6 % uncertainty in plot level estimation of AGB in tropical forests but did not include the effects of errors in the measurement of other parameters such as DBH.

Individual tree biomass should be the functions of DBH, tree height, and wood specific density (Chave et al., 2005). Therefore, a number of allometric models had been developed using only these three parameters (Chave et al., 2005; Vieilledent et al., 2012; Lima et al., 2012; Manuri et al., 2014). Because some forest inventories failed to measure tree height and/or wood specific density, allometric models had also been developed without these parameters (Chave et al., 2005; Vieilledent et al., 2012; Lima et al., 2012; Manuri et al., 2014). In many cases, researchers had assessed the errors of these allometric models during the process of model development (e.g. Chave et al., 2005; Manuri et al., 2014). Therefore, many studies had assessed the errors caused by these individual types of allometric models.

Tree height is one of the most important parameters used to estimate individual tree biomass. Chave et al. (2005) reported that the addition of tree height improved the quality of allometric models. Lima et al. (2012) compared six allometric models and showed that an allometric model including tree height achieved the highest R^2. However, these results include some errors caused by allometric models and do not take into account errors in physical measurements. Measuring tree height is often a difficult task and may potentially contain large errors, especially in a forest with tall trees having dense crowns, such as tropical forests. For example, Larjavaara & Muller-Landau (2013) quantified the tree height measurement error in a moist tropical forest and documented several cases of severe overestimation of tree height by more than 100 %. Therefore, allometric models including tree height (i.e. three-parameter models) may be inferior to those excluding tree height (i.e. two-parameter models), when errors in measurements are considered. In a limited research study, although Hunter, Keller, Victoria, & Morton (2013), reported on the effects of errors in tree height measurement on plot level biomass estimation, as described above, their study did not take into account the errors caused by allometric model. Therefore, the comprehensive research study that includes both errors caused by tree measurement error and errors caused by the allometric model are needed.

The aim of this study is to evaluate the importance of tree height during the estimation of individual tree biomass when both types of errors are considered. First, two sets of field data collected on the same trees from two different field crews are employed to quantify measurement errors of DBH and tree height in a tropical forest. Then, the uncertainty of individual tree biomass estimated by a three-parameter model (i.e. an allometric model composed of DBH, tree height, and wood specific density data) and that by a two-parameter model excluding tree height (i.e. an allometric model composed of only DBH and wood specific density data) are compared by using error propagation theory.

MATERIALS AND METHODS

Field Measurement

Field data collected in Kampong Thom Province, central Cambodia, was used to evaluate the measurement error. This province is located between 12°11′–13°26′N, 104°12′–105°44′E, covered 12,447 km^2 of land area or about 7 % of Cambodia. The province has relatively uniform geographical and ecological conditions; for example, high humidity persists throughout the year (72–87 %; annual mean, 80 %). The monsoonal wind systems experience a bi-annual change in this tropical climate. The rainy season (May to October) is followed by a dry season that lasts the remainder of the year.

Two plots measuring 30 m × 30 m (0.09 ha) were established in evergreen forest, and two different measurement teams were formed that composed of technicians with extensive field experience. Each measurement team independently collected the field data of two plots in November 2011, including DBH and tree height for all trees with DBH > 5 cm (Table 1). Both the teams used Vertex-III instruments (Haglöf Company Group, Långsele, Sweden) for tree height measurement and measuring tapes for DBH.

Table 1. Summary of field data collected by two measurement teams

Parameters		Team 1	Team 2
The number of trees (N)		248.0	248.0
DBH (cm)	Minimum	5.0	5.0
	Mean	12.7	12.8
	Maximum	67.5	66.9
Tree height (m)	Minimum	4.4	4.6
	Mean	13.2	13.4
	Maximum	34.8	35.5

Felling Data

The destructive sampling data from (Hozumi, Yoda, Kokawa, & Kira, 1969) was used to provide "accurate" data for AGB to assess the uncertainty of individual tree biomass estimation. The felling data had been collected from 72 trees in an old growth forest located in Koh Kong Province in southwest Cambodia. The felling data was also used as materials related to the allometric model developed by Chave et al. (2005). One tree (Barringtonia spp.) was excluded from datasets, because it was apparently a resprout (height 2 m for a DBH of 7.4 cm) and Chave et al. (2005) also excluded that tree. Ultimately, there were 71 trees used in this analysis. Note that the DBH and tree height of the felling data and field data were comparable (Table 2), while two data used, were collected from different sites, were used

Table 2. The comparison of field measurement data and felling data

Parameters		Field measurement data	Felling data
DBH (cm)	Mean	12.8	11.6
	Standard deviation	10.4	16.4
Tree height (m)	Mean	14.0	11.5
	Standard deviation	6.1	5.8

Remarks: Values of the field measurement were calculated assuming that the mean of two measurements were standard value

These data included local tree name, DBH, tree height, dry weight of trunk, dry weight of branches, and dry weight of leaves. The total dry weight was calculated by adding the dry weight of the trunk, branches and leaves. Wood specific density of each tree was derived from the Global Wood Density database (Chave et al., 2009; Zanne et al., 2009). The data of Hozumi, Yoda, Kokawa, & Kira (1969) included the genus but not the species for 34 trees. The average wood density for the genus was used when the genus name was available. If the genus was not available, 0.56 was used because Chave et al. (2005) used 0.56 for unknown tree species for the data of Hozumi, Yoda, Kokawa, & Kira (1969).

Allometric Equations

Two allometric models developed by Chave et al. (2005) were selected for three reasons. First, both three- (with tree height) and two-parameter (without tree height) models exist and were selected to compare the effects of tree height. Second, allometric models had been developed using data sets of tropical forests from 27 study sites including a study site in Cambodia. Because of the research study sites are also in Cambodia, it is assumed that the selection of allometric models which used the data sets from Cambodia was reasonable. Third, allometric models have been widely used and reported as authentic model for measuring tree biomass (Vieilledent et al., 2012; Fayolle, Doucet, Gillet, Bourland, & Lejeune, 2013; Manuri et al., 2014; Lambrick, Brown, Lawrence, & Bebber, 2014).

AGB estimation using pan-tropical equations occasionally increased the bias when compared with the estimation of biomass using region-specific models (Basuki, van Laake, Skidmore, & Hussin, 2009). However, the pan-tropical allometric models developed by Chave et al. (2005) perform equally well as region-specific equations (Vieilledent et al., 2012; Fayolle, Doucet, Gillet, Bourland, & Lejeune, 2013; Manuri et al., 2014). Therefore, the allometric models were decided as dependable models.

Chave et al. (2005) developed their allometric models based on climate patterns. In this study, the allometric models were used for the wet region of Chave et al. (2005) because felling data were the materials used in those wet region models. The three- and two-parameter models for the wet region were expressed by Equations (1) and (2), respectively:

$$AGB_e = 0.0776(\rho D^2 H)^{0.94} \quad (1)$$

$$AGB_e = \rho \exp(-1.239 + 1.98 \ln D + 0.207(\ln D)^2 - 0.0281(\ln D)^3) \quad (2)$$

where AGB_e was estimated AGB, ρ was wood specific density, D was DBH (cm), and H was tree height (m)

Overview of Methods

In this study, the uncertainty of individual tree biomass estimation of felling trees was calculated, assuming that the felling trees were measured using Vertex-III instruments for tree height measurement and measuring tapes for DBH. The uncertainty of individual tree biomass estimation caused by errors in measurement and caused by the use of specific allometric models were calculated. Finally, the overall uncertainty of individual tree biomass was calculated by combining the two uncertainties.

The methods based on error propagation theory were used to quantify the uncertainty of individual tree biomass following Berger, Gschwantner, McRoberts, & Schadauer (2014) who provided detailed descriptions of the methodology. Briefly, the methodology quantified the uncertainty in terms of the relative standard deviation (SD), and was composed of four parts (Fig. 1). First, the SD of the measurements from field measurement data was calculated. Then, the relative SDs derived from errors in measurement and from both allometric models were calculated using error propagation theory from felling data. Finally, by combining these relative SDs, the relative SD of individual tree biomass estimation was calculated.

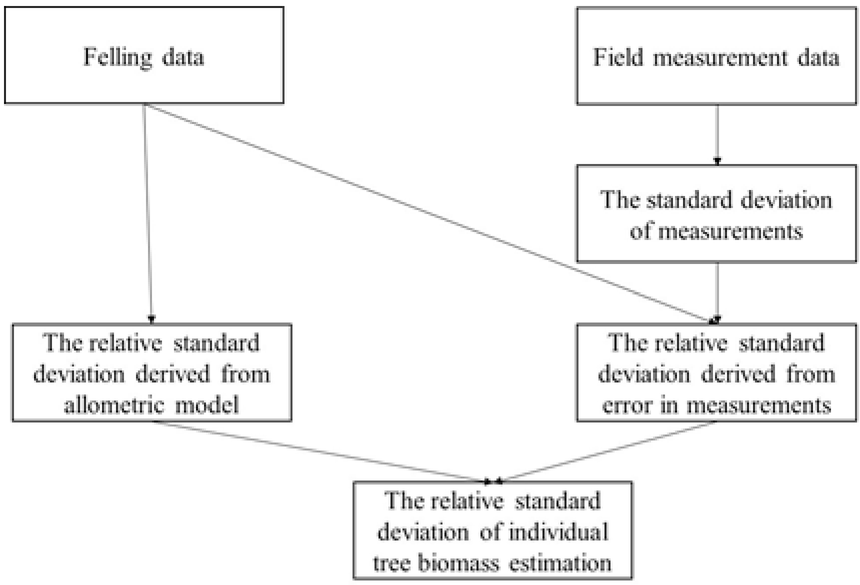

Fig. 1. Overview of the process

The SD of Measurements

Berger, Gschwantner, McRoberts, & Schadauer (2014) showed that a relationship exists between the SD and the size of tree. Therefore, the relationship between the SD and size for each measurement parameter (i.e. DBH and tree height) were checked. Then, when a relationship was found, a regression model estimating the SD based on the tree size was created by linear regression. the SD of the measurement from field survey data was calculated, selecting a similar procedure to that used by Berger, Gschwantner, McRoberts, & Schadauer (2014). First, the measurement data were grouped by *n* trees (in this research case, ten) in ascending order with respect to the mean of the two measurements. For each group, the mean and the SD of measurement differences were calculated following Berger, Gschwantner, McRoberts, & Schadauer (2014). Then, the Pearson's correlation between the SD of measurement differences and the mean size of the class was calculated. If the correlation was not significant ($p \geq 0.05$), it was assumed that the SD was constant and not related to the size of tree. In this case, the SD of measurement differences (Y) was calculated using Equation (3):

$$Y = \overline{SD_{x_i}} \tag{3}$$

where x_i was the i^{th} measurement parameter, $\overline{SD_{x_i}}$ was the average of the SD of measurement differences of the i^{th} measurement parameter. If the correlation was significant ($p < 0.05$), the SD of the measurement differences of each class was regressed against the mean of the class using a linear regression expressed as Equation (4):

$$Y = \beta_1 + \beta_2 X \tag{4}$$

where β_1 and β_2 were the parameters to be estimated, and X was the class mean. Note that Berger, Gschwantner, McRoberts, & Schadauer (2014) used a nonlinear regression model to express the relationship between the SD of measurement differences of each class and the mean of the class. Both linear and nonlinear models were tested and concluded the linear model was better than the nonlinear model in terms of root mean squared error. Therefore, the linear model was selected. The SD of measurement differences were divided by $\sqrt{2}$ to calculate the SD of the measurement, because the SD of measurement differences was calculated from the difference of two random variables (Berger, Gschwantner, McRoberts, & Schadauer, 2014).

Note that this study focused on the error in the measurement of tree height and DBH, while the SD of wood specific density was ignored. It occurred because the aim of this study was to evaluate the importance of tree height in the estimation of individual tree biomass; therefore, wood specific density was unrelated to this topic.

The SD Derived from Measurement Error

The SD derived from measurement error ($SD_{AGB,\,m}$) could be calculated by Equation (5):

$$SD_{AGB,m} = \sqrt{\sum_i \left(\frac{\partial AGB}{\partial x_i} SD_{x_i}\right)^2} \tag{5}$$

where $\frac{\partial AGB}{\partial x_i}$ were the first derivatives of the expression for AGB, assigning the measurement errors were pairwise independent from each other (Berger, Gschwantner, McRoberts, & Schadauer, 2014). The equation was based on the error propagation theory, which used a Taylor series approximation. For the three-parameter model, the first derivatives were expressed by Equations (6) and (7):

$$\frac{\partial AGB}{\partial D} = 0.145888\, \rho^{0.940} D^{0.880} H^{0.940} \tag{6}$$

$$\frac{\partial AGB}{\partial H} = 0.072944\, \rho^{0.940} D^{1.880} H^{-0.060} \tag{7}$$

Also, the first derivatives for the two-parameter model were expressed by Equation (8):

$$\frac{\partial AGB}{\partial D} = \rho D^{0.95}(-0.0244195 * (\ln D)^2 + 0.119925 \ln D + 0.573554)\exp(0.207(\ln D)^2 - 0.0281(\ln D)^3) \tag{8}$$

The relative SD derived from measurement error ($SD_{AGB,\,m,\,r}$) was expressed as Equation (9):

$$SD_{AGB,m,r} = \frac{SD_{AGB,m}}{AGB_t} \tag{9}$$

where AGB_t was true AGB. For each harvested tree collected by Hozumi, Yoda, Kokawa, & Kira (1969), the relative SD derived from measurement error was calculated.

The SD Derived from Allometric Equation

The relative error caused by the allometric equation was calculated for each tree as Equation (10):

$$e_{a,r} = \frac{AGB_e - AGB_t}{AGB_t} \quad (10)$$

where $e_{a,r}$ was the relative error caused by the allometric equation (Berger, Gschwantner, McRoberts, & Schadauer, 2014). In this study, the felling data of Hozumi, Yoda, Kokawa, & Kira (1969) was used to calculate the relative error caused by the allometric equation. It is assumed that the total dry weight calculated from felling data of Hozumi, Yoda, Kokawa, & Kira (1969) represented the true AGB. The relative error caused by the three-parameter allometric equation and that caused by the two-parameter model were calculated separately, assuming that the AGB calculated using Equations (1) and (2) were assumed to be the AGBe. From ea,r, the relative SD derived from the allometric model (SDAGB, a, r) was calculated for each allometric equation.

The Relative SD of Individual Tree Biomass

The total variance of the individual tree biomass estimate was calculated by adding the variance derived from both the measurement error and the allometric model (Berger, Gschwantner, McRoberts, & Schadauer, 2014):

$$\mathrm{Var}(AGB) = \mathrm{Var}(e_m) + \mathrm{Var}(e_a) \quad (11)$$

where Var(AGB) was the total variance of the individual tree biomass, Var(e_m) was the variance derived from the measurement error and Var(e_a) was the variance of the allometric model. The relative SD of individual tree biomass was expressed by Equation (12):

$$SD_{AGBr} = \sqrt{SD^2_{AGBmr} + SD^2_{AGBar}} \quad (12)$$

The relative contribution of each measurement error and the allometric model for the total variance of the individual tree biomass following Berger, Gschwantner, McRoberts, & Schadauer (2014) were also quantified.

RESULTS AND DISCUSSION

Table 3 showed the correlation between the SD of measurement differences of each class, the mean size of the class and the estimates of parameters. The SD of DBH measurement was not significantly correlated with the size of DBH ($p > 0.05$). Therefore, it was assumed that the SD of DBH measurement was constant. Otherwise, the SD of tree height measurement was significantly correlated with the tree height ($p < 0.05$). The SD of tree height was regressed against the tree height. Finally, the estimated SD of each parameter was found using Equations (13) and (14):

$$SD_{DBH} = 0.13 \quad (13)$$

$$SD_{height} = 0.20{+}0.12H \quad (14)$$

Table 3. Pearson's correlation coefficients between differences in standard deviation of measurement, tree size and estimates of parameters

	Pearson's correlation coefficient	P value	SD_{x_i}
DBH	0.14	0.51	0.13
Tree height	0.55	0.01	0.20+0.12H

Remarks: was the standard deviation; H was tree height.

Table 4 presented the relative SD of the individual tree biomass. In the case of the relative SD derived from allometric model, the relative SD from three- and two-parameter models were 0.33 and 0.35, respectively. It indicates that the three-parameter model was 6 % (i.e. (0.33-0.35)/0.35*100) more accurate than two-parameter model when the uncertainty caused by the allometric model was the only consideration.

Table 4. Relative standard deviation from measurement error, from an allometric model, and of individual tree biomass

	$SD_{AGB, m, r}$	$SD_{AGB, a, r}$	$SD_{AGB, r}$
Three-parameter model	0.16	0.33	0.37
Two-parameter model	0.05	0.35	0.35

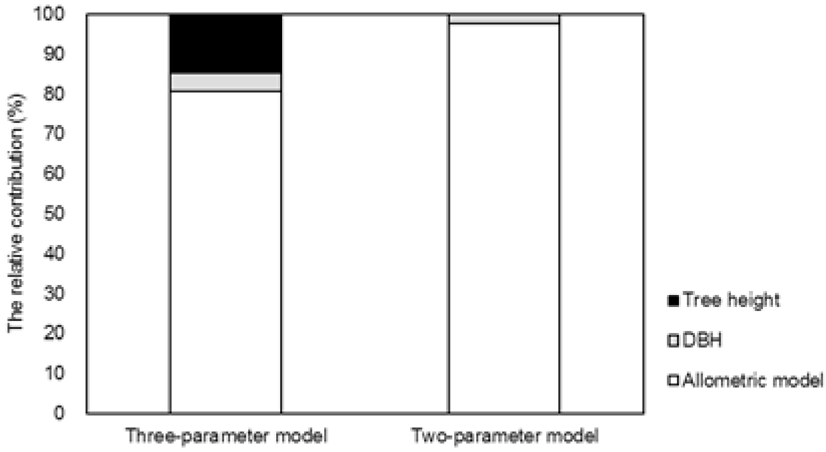

Fig. 2. Contributions to the overall variance (%)

Furthermore, in the case of the relative SD derived from the measurement error, the SDs from the three-and two-parameter models were 0.16 and 0.05, respectively. It meant that the three-parameter model was inferior to the two-parameter model in terms of the uncertainty caused by tree measurement. Finally, the total relative SDs of the three- and two-parameter models were 0.37 and 0.35, respectively, indicating that the two-parameter model was more accurate than the three-parameter model. It indicated that the two-parameter model was 5 % (i.e. (0.35-0.37)/0.37*100) more accurate than three-parameter model when the uncertainty caused by the allometric model and that caused by measurement error were considered.

Fig. 2 showed the contribution to the overall variance. The greatest contributor to the overall variance was the allometric model itself for both the three- and two-parameter models. The percentages that the allometric model contributed to the overall variance for three- and two-parameter models were 81 % and 98 %, respectively. Tree height was the second greatest contributor to the overall variance for the three-parameter model, contributing 14 % of the overall variance. The percentages that DBH contributed to overall variance for three- and two-parameter models were 5 % and 2 %, respectively.

Several studies had demonstrated the value of tree height to the estimation of AGB of individual trees (Chave et al., 2005; Lima et al., 2012). However, measuring tree height accurately was difficult especially in forests with tall and dense crowns (Larjavaara & Muller-Landau, 2013). In this study, the importance of using tree height was evaluated to estimate individual tree biomass when both the errors caused by measurement and by use of an allometric model were considered. The measurement errors of DBH and tree height in a tropical forest were quantified and the uncertainty of individual tree biomass estimated by the allometric model both including and excluding tree height from the model were compared. Since it was impossible to measure DBH and tree height without any uncertainty, true DBH and tree height as well as true measurements error cannot be quantified. This study used the mean of two measurements as the standard value instead of true DBH and tree height. Measurement errors were quantified using the difference of two measurements from the standard value. Thus, the measurement errors calculated in this study have the possibility to differ from true measurements error.

The allometric model including tree height was more accurate than to the allometric model excluding tree height in terms of the relative SD derived from the allometric model (Table 4). However, the addition of tree height into the allometric model increased the relative SD derived from tree parameter measurements (Table 4). As a result, in terms of the total relative SD of individual biomass estimation, the allometric model excluding tree height proved to be a better choice than the allometric model including tree height (Table 4).

This result implies that tree height was not informative to the estimation of individual tree biomass when both the errors caused by measurement and the allometric model were considered. Previous studies demonstrated that the allometric model including tree height showed more accurate estimation comparing to the model excluding tree height (Chave et al., 2005; Lima et al., 2012; Feldpausch et al., 2012). However, these research studies did not consider errors caused by problems related to tree height measurement. This study showed that the errors in tree height measurement may potentially result in an increase in errors in the estimation of AGB. The researchers should decide whether the allometric model including or not including tree height was used by considering not only the allometric model itself but also the difficulty of tree height measurement. Here, it was important to note that the researchers did not deny the importance of tree height. As previous studies suggested, tree height improved the individual biomass estimation in terms of the relative SD derived from an allometric model (Table 4). However, the improvement was only 6 %. It indicated that tree height was not necessarily informative in terms of the relative SD derived from an allometric model. Feldpausch et al. (2012) evaluated the effects of incorporating tree height on AGB estimation in terms of the error caused by allometric models across the continents. They showed that the importance of tree height varies from region to region and the inclusion of tree height in an allometric model did not substantially modify the estimates based on an allometric model without tree height in the Asian region. Therefore, the results of the present study may underestimate the importance of tree height when comparing data from the present study region with the results in other regions. Also, in terms of the total relative SD, although the allometric model excluding tree height provided improved results when compared with the allometric model including tree height, the improvement was only 5 %. Therefore, even if the error caused by measurement was considered, it was possible that the inclusion of tree height may reduce the error in the estimation of individual tree biomass in other regions where tree height was informative in terms of the uncertainty caused by an allometric model.

The allometric model itself made the greatest contribution to the overall variance (Fig. 2). It implied that the selection of an appropriate model was the most important factor in accurately estimating individual tree. Previous studies exposed the same finding; that was, the allometric model itself was the greatest contributor to the overall variance (Chave et al., 2004). This study also demonstrated the extent of the contribution of the allometric model to the uncertainty of individual biomass estimation. Different allometric models were often available at the same site that could be used to estimate the individual tree biomass. Manuri et al. (2014) compared the estimation accuracy of ten existing allometric models and showed that these allometric models led to very different estimates of individual tree biomass. Because the error derived from allometric models contributed more than 80 % of the overall variance, if individual tree biomass wanted to be accurately estimated, much time should be spent as is reasonable and enormous effort when selecting the appropriate allometric equation. It should be also noted that the contribution of DBH measurement error of three -parameter model was larger than that of two-parameter models. The result implied that three-parameter model was more vulnerable to the measurement errors. Thus, the accuracy of measurement should be taken into account when selecting the appropriate allometric equation. The errors in tree height measurement contributed 14 % of the overall variance (Fig. 2). Previous studies had shown errors in tree height measurement had had only limited effects on the estimation of AGB (e.g. Hunter, Keller, Victoria, & Morton, 2013). The present study also demonstrated the limited effects of errors in tree height measurement when compared with the effects of allometric models. However, the precision of tree height measurement was affected by the methods used (Larjavaara & Muller-Landau, 2013), as well as by tree height itself (Hunter, Keller, Victoria, & Morton, 2013), tree species (Kitahara, Mizoue, & Yoshida, 2008), and training levels of the field personnel (Kitahara, Mizoue, & Yoshida, 2010). Therefore, the effect of tree height measurement error might increase in some conditions. Further investigation was required on the effects of the evaluation of tree height on the estimation of individual tree biomass in other conditions. The further investigation was also needed.

CONCLUSION AND SUGGESTION

It can be concluded that errors in tree height measurement have the potential to cause additional errors in the estimation of AGB. Therefore, unreliable tree height measurements are not informative. When estimating AGB, it should be decided whether to include tree height in the allometric model, because of the difficulty of accurately measuring tree height.

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