



Allometric Biomass Model for *Aquilaria Malaccensis* Lam. in Bangladesh: A Nondestructive Approach

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ABSTRACT

Aquilaria malaccensis Lam. is an important commercial tree species of Bangladesh. This species is widely planted for the increased demand for an essential oil locally known as “Agar”. A nondestructive method was adopted to derive the allometric biomass model for *A. malaccensis*. Stem volume of 254 trees and the model of biomass expansion factor (BEF) were used to estimate the total above-ground biomass (TAGB). A total of five allometric equations with natural logarithm were tested to derive best-fit biomass models for crown, stem, and total above-ground biomass (TAGB). The best-fit allometric model was selected based on the lowest value of akaike information criteria (AIC), residual standard error (RSE), and the highest value of the coefficient of determination (R^2) and akaike information criteria weighted (AICw). The best-fit model of BEF was $BEF = \exp(2.112318 - (DBH \cdot TH)^{0.1066121})$. The best-fit allometric biomass models for crown, stem and TAGB were crown biomass = $\exp(-0.6031 + 0.4279 \cdot \ln(DBH^2 \cdot TH))$, stem biomass = $\exp(-3.2483 + 1.7910 \cdot \ln(DBH) + 0.7881 \cdot \ln(TH))$ and TAGB = $\exp(-1.9121 + 1.5937 \cdot \ln(DBH) + 0.6152 \cdot \ln(TH))$. The best-fit TAGB model showed the highest efficiency in biomass estimation compared to commonly used pan-tropical biomass models in terms of model prediction error (MPE), model efficiency (ME).

KEYWORDS

Allometry; *Aquilaria malaccensis*; biomass; biomass expansion factor

Introduction

The *Aquilaria malaccensis* Lam. is a native tree species of Bangladesh (Lee & Mohamed, 2016). This species has important commercial value for the extraction of aromatic resin which locally known as “Agar”. Agar is a highly priced product, which is used for fragrance, incense, medicines aromatherapy, and religious ceremonies (Talucder et al., 2016). Bangladesh earns about 3.75 million U.S. dollars yearly from the export of agar oil and it became the most promising non-timber forest products of Bangladesh (Hayder et al., 2005). Infested heart wood of *A. malaccensis* serves as raw material for agar oil distillation. Therefore, the whole tree is sacrificed for searching for

agarwood. This resulted in a considerable reduction of natural patches of *A. malaccensis* in Bangladesh (Lee & Mohamed, 2016).

With the increasing demand for “Agar” (extract of *A. malaccensis* wood), different non-government organizations (NGOs), private planters, and Bangladesh Forest Department (BFD) have initiated plantation of *A. malaccensis* at the northeast and southeast hilly areas of Bangladesh (Akter et al., 2013). Felling of infested *A. malaccensis* trees is the only way to extract “Agar” from its wood chips through the distillation process. Unfortunately, there is no record on the yearly harvested biomass of *A. malaccensis* from the plantations in Bangladesh. Reducing emissions from deforestation and forest degradation is a major concern of REDD+ activities around the globe for conserving forests and protecting biodiversity (Mukul et al., 2014). The production of “Agar” and the REDD+ initiatives are vice versa. As part of REDD+ initiatives, it is important to track the harvested amount of *A. malaccensis*, stock in the plantation sites, and degradation due to harvest. In response to this situation, we need to develop a scheme for the sustainable planting and management of *A. malaccensis*, which can be achieved through the studies on biomass and volume stock, and increment assessment, and net primary productivity, nutrient cycling, and budget assessment in the plantation of this species in Bangladesh.

Biomass estimation can be carried out by using three methods: the destructive, the nondestructive, and the mean tree method. Both the destructive and nondestructive techniques provide data for the allometric method of model development (Golley et al., 1975; Ketterings et al., 2001). However, the destructive method, on one hand, requires destructive felling of trees, and the mean tree method is suitable for the plantation (Ketterings et al., 2001). Nevertheless, the allometric technique is a semi- or nondestructive method that frequently used for biomass estimation where the whole or partial weight of a tree can be estimated from measurable tree dimension (stem diameter and height) (Ketterings et al., 2001; Komiyama et al., 2005; Picard et al., 2012). The semi- or non-destructive approach in allometric model development is cost-effective and less time-consuming to estimate biomass of tree species in either a forest or plantation (Picard et al., 2012). Conversely, the semi- or nondestructive method is not much accurate and precise compared to the destructive method (Njana, 2017).

Allometric biomass models can be of different types such as pan-tropical or regional, site-specific common, species-specific, etc. (Mahmood et al., 2019). The applicability and accuracy of these types of biomass models are highly variable (Sileshi, 2014). Species-specific biomass model can estimate biomass efficiently (Maulana, 2014; Ngomanda et al., 2014). However, biomass models for *A. malaccensis* are lacking in existing literature while this species is well distributed in Bangladesh (Mahmood et al., 2016a) and neighboring countries (Sandeep et al., 2014). *Aquilaria malaccensis* is a valuable species of Bangladesh and has some restrictions on felling. Hence, the semi- or nondestructive method can be used to develop an allometric biomass model considering the uncertainties of using this method (e.g., Njana, 2017; Njana et al., 2016). However, this study aimed to i) develop allometric biomass models for *A. malaccensis* use the nondestructive method in Bangladesh ii) test the performance of models with different independent variables (Diameter as Breast Height, Total Height, and Wood Density) iii) compare the performance of the best-fitted model with the frequently used regional and pan-tropical biomass models.

Materials and methods

Description of the study area

The plantations of *A. malaccensis* are distributed in the northeastern and southeastern hilly forest areas of Bangladesh (Figure 1). The study area contains tropical evergreen and semi-evergreen tree species with natural and plantation stands. The temperature during the monsoon and winter varies from 20°C to 36°C and 8°C to 15°C, respectively. The mean annual rainfall of the study area found to vary from 2500 mm to 5800 mm (Khatun et al., 2016). Soil is acidic, yellowish-brown to reddish-brown, loam to clay loam, and sandy clay loam. Soil organic matter varies from 0.15% to 3.32% (Hossain et al., 2014).

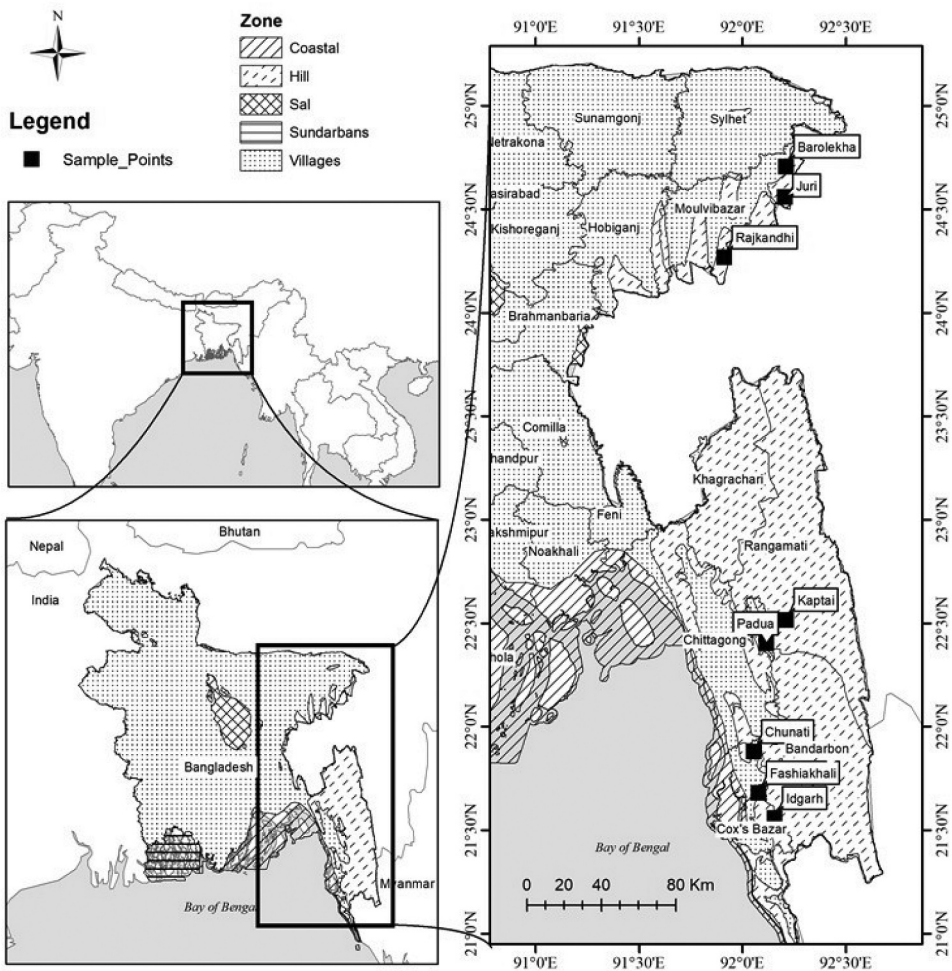


Figure 1. Map of the study area.

Biomass expansion factor (BEF)

Sampling and field measurement of sampled trees

Fifteen sample trees of *A. malaccensis* were selected purposively from the study area to cover a range of Diameter at Breast Height (DBH) and Total Height (TH) of 8 to 41 cm and 4 to 20 m, respectively. DBH and TH of the sampled trees were measured and the nondestructive method was used to estimate the volume of stems and bigger branches (diameter >7 cm). The sampled trees were climbed; the stem and the bigger branches (Diameter >7 cm) were marked into suitable log sections. The diameters at thicker and thinner ends of each section of stem and bigger branches, and the base diameter of all smaller branches (Diameter <7 cm) were measured using diameter tape or caliper according to Picard et al. (2012) and Mahmood et al. (2019). Finally, the volume of the individual log section was estimated using Smalian’s formula (Equation 1) and volumes of each log section were summed to get the total volume of that particular sampled tree.

$$\text{Smalian's formula}(V) = \frac{\pi L(D_1^2 + D_2^2)}{8} \tag{1}$$

where V = volume in m³, π = 3.143, L = Length of the log section (m), D₁² = Diameter at the thicker end (m), D₂² = Diameter at the thinner end (m)

Biomass of sample trees

Biomass of stem and bigger branches of the sampled trees were measured from their volume and mean wood density values (320 kg/m³, Zanne et al., 2009). Wood and bark density varies along the length from base to top of the stem and bigger branches. Moreover, it also varies from the periphery to the pitch of the stem and branch and age of the tree (Picard et al., 2012). This study did not consider the bark density as well as variations in wood density. Therefore, biomass estimates from this study have a certain level of uncertainties. The biomass of smaller branches of each smaller tree was estimated from the branch allometric models derived by Mahmood et al. (2019) (Table 1).

Models of biomass expansion factor (BEF)

Biomass expansion factor (BEF) of the individual sampled tree was calculated according to Taeroe et al. (2015), where a ratio was obtained from the total aboveground biomass (TAGB) containing biomass of stem, bigger branches, smaller branches, and leaves) and stem biomass stood alone for a tree. Six models (BEF = a* exp (DBH*b), BEF = a*exp (TH*b), BEF = exp (a – (DBH*TH)^b), BEF = a – (DBH*TH)^b, BEF = a – (DBH^2*TH)^b, and BEF = a – (DBH*TH^2)^b; where DBH = Diameter at breast height, TH = Total height) related to tree dimensions were used to derive BEF models according to Sanquetta et al. (2011) and Longuetaud et al. (2013). The best-fit model of BEF was selected by

Table 1. Branch allometric models for *Aquilaria malaccensis*. Source: Mahmood et al. (2019).

Branch parts	Allometric model	Adjusted R2
Leaf	Ln (biomass) = –4.3355 + 1.8418*Ln (Base dia)	0.6588
Leaf containing smaller branch	Ln (biomass) = –4.6118 + 1.8418*Ln (Base dia)	0.6588
Woody part of branches	Ln (biomass) = –4.4371 + 2.7251*Ln (Base dia)	0.8996

comparing the Akaike Information Criterion (AIC) and RMSE value of each model (Longuetaud et al., 2013).

Allometric equation

Data collection and compilation

This study used only the stem volume (excluding the bigger branch) raw data of 254 individuals of *A. malaccensis*, which was utilized to develop volume tables by Bangladesh Forest Research Institute. The ranges of DBH and total height were 8 to 42 cm and 4 to 20 m, respectively (Islam & Chowdhury, 2017). Stem biomass (kg) of the individual sampled tree was estimated from their calculated stem volume (m^3) and overall wood density (kg/m^3) value as derived from the database Zanne et al. (2009). Finally, the total above-ground biomass (TAGB) of individual trees was estimated from the stem biomass and the derived best-fit BEF model (Soares & Tome, 2012). However, existing studies indicate that indirect methods of biomass estimation employed in this study have varying levels of uncertainties (Njana, 2017; Njana et al., 2016). Another source of uncertainty is expected from the variation between the threshold top diameter limit for the stems of the sampled trees and the stems of the study of Islam and Chowdhury (2017). The independent variables (DBH, TH, and WD) and dependent variable (TAGB) were transformed to Ln (natural logarithm) to improve the linearity and homoscedasticity. The total data set (254 individuals) was divided into data Sets A and B. Data Set A contained randomly selected 204 individuals, which was used to derive the allometric model. The Data Set B contained the rest of 50 individuals. This Data Set B was used for validating the fitted model generated by Data Set A and comparing the model performance with frequently used regional and pantropical biomass models.

Allometric model

A total of five allometric models ($\text{Ln}(\text{Biomass}) = a + b \cdot \text{Ln}(\text{DBH})$; $\text{Ln}(\text{Biomass}) = a + b \cdot \text{Ln}(\text{DBH}) + c \cdot \text{Ln}(\text{TH})$; $\text{Ln}(\text{Biomass}) = a + b \cdot \text{Ln}(\text{DBH}) + c \cdot \text{Ln}(\text{WD})$; $\text{Ln}(\text{Biomass}) = a + b \cdot \text{Ln}(\text{DBH}^2 \cdot \text{TH})$ and $\text{Ln}(\text{Biomass}) = a + b \cdot \text{Ln}(\text{DBH}^2 \cdot \text{WD})$) were deriving the best-fit allometric model for estimating crown, stem, and total above-ground biomass. Here crown included the biomass of bigger branches, smaller branches, and leaves. As all the tested models used natural logarithm transformation, a correction factor (CF) was calculated for each equation to minimize the systematic bias during the back transformation to biomass value (Sprugel, 1983). The model having the lowest Akaike Information Criterion (AIC) and Residual Standard Error (RSE); and the highest Akaike Information Criterion Weight (AICw) and coefficient of determination (R^2) values were considered as best-fit model (Mahmood et al., 2016b, 2019; Picard et al., 2015; Sileshi, 2014). Data analysis was done using R statistical software.

Model comparison

Best-fit TAGB model was compared with the frequently used regional and pan-tropical models (Table 2) in terms of Model Prediction Error (MPE), Model Efficiency (ME), and Root Mean Square Error (RMSE) (Mayer & Butler, 1993). This comparison was conducted with Data Set B.

Table 2. Frequently used regional and pan-tropical allometric biomass models.

Source	Allometric biomass model	Type
Brown (1997)	$TAGB = \exp(-2.134 + 2.5430 \cdot \ln(DBH))$	Pan-tropical
Nelson et al. (1999)	$TAGB = \exp(-1.8985 + 2.1569 \cdot \ln(DBH) + 0.3888 \cdot \ln(TH) + 0.7218 \cdot \ln(WD))$	Central amazon
Chave et al. (2005)	$TAGB = WD \cdot \exp(-1.499 + 2.148 \cdot \ln(DBH) + 0.207 \cdot (\ln(DBH))^2 - 0.0281 \cdot (\ln(DBH))^3)$	Pan-tropical
Brown et al. (1989)	$TAGB = \exp(-2.4090 + 0.9522 \cdot \ln(DBH^2 \cdot TH \cdot WD))$	Pan-tropical
Chave et al. (2014)	$TAGB = \exp(-2.6986 + 0.976 \cdot \ln(DBH^2 \cdot TH \cdot WD))$	Pan-tropical

$$MPE(\%) = \frac{100}{n} \times \sum \left[\frac{(Y_p - Y_o)}{Y_o} \right] \quad (2)$$

$$ME = 1 - \left[\frac{\sum (Y_o - Y_p)^2}{\sum (Y_o - \bar{Y})^2} \right] \quad (3)$$

$$MSE(\%) = 100 \times \sqrt{\frac{1}{n} \sum_{i=1}^n (Y_p - Y_o)^2} \quad (4)$$

where n = Number of trees, Y_p = Predicted biomass from the model, Y_o = Observed biomass in field measurement, and $\bar{Y}$ = Mean of the observed biomass.

Regression between predicted biomass (Y_p) (in the X-axis) and observed biomass (Y_o) (in the Y-axis) were also derived for the best-fit TAGB model, and frequently used pan-tropical and regional models of TAGB (Table 2). Significance of slope ($b = 1$) and intercept ($a = 1$) were tested (Pinheiro et al., 2008) to understand the overestimation or underestimation of each predicted biomass value from observed value by using 1:1 line (Sileshi, 2014).

Result

Biomass expansion factor BEF

Model 3 was the best-fit biomass expansion model ($BEF = \exp(2.1123189 - (D \cdot H))^{0.1066}$) having lowest value of AIC (1.6106) and RMSE (0.1689) and highest R^2 (0.4331) value (Table 3).

Table 3. Comparison of the derived models of biomass expansion factor (BEF).

Model no	Formula	a	b	RMSE	AIC	RSE	Adjusted R2
1	$BEF = a \cdot \exp(DBH \cdot b)$	1.9486	-0.0161	0.1726	3.2170	0.1797	0.3585
2	$BEF = a \cdot \exp(TH \cdot b)$	1.9575	-0.0293	0.1717	3.0733	0.1787	0.3656
3	$BEF = \exp(a - (DBH \cdot TH)^b)$	2.1123	0.1066	0.1623	1.6106	0.1689	0.4331
4	$BEF = a - (DBH \cdot TH)^b$	3.3661	0.1246	0.1657	2.1562	0.1725	0.4088
5	$BEF = a - (DBH^2 \cdot TH)^b$	3.3919	0.0818	0.1661	2.2187	0.1729	0.4059
6	$BEF = a - (DBH \cdot TH^2)^b$	3.3336	0.0841	0.1660	2.2017	0.1728	0.4067

Allometric biomass model selection

Model 4 for crown biomass (Crown biomass = $-0.6031 + 0.4279 \ln(\text{DBH}^2 \cdot \text{TH})$) was best-fit model with lowest value of AIC (-176.169) and RSE (0.1556); and highest value of adjusted R^2 (0.8554) and AICw (0.6433) compared to its close competitor Model 2 (Table 4). The best-fit biomass model for stem was model 2 (Stem biomass = $-3.2483 + 1.7910 \ln(\text{DBH}) + 0.7881 \ln(\text{TH})$) having lowest AIC (-286.955) and RSE (0.1183); and highest adjusted R^2 (0.9763) and AICw (0.5329). Similarly, model 2 was also the best-fit model for TAGB (TAGB = $-1.9121 + 1.5937 \ln(\text{DBH}) + 0.6152 \ln(\text{TH})$) with the lowest AIC (-283.737) and RSE (0.1192); and highest adjusted R^2 (0.9675) and AICw (0.8959) (Table 4).

Model comparison

The TAGB best-fit model showed lowest (-0.1%) MPE and RMSE (1109.69) and highest ME (0.934 close to the reference value 1) compared to the frequently used pan-tropical and regional biomass models of Brown et al. (1989), Brown (1997), Nelson et al. (1999), Chave et al. (2005, 2014) (Table 5). The graphical presentation from 1:1 line indicated that the best-fit TAGB model 2 was capable to estimate the total aboveground biomass more accurately. While frequently used pan-tropical and regional allometric biomass models overestimated the TAGB for *A. malaccensis* compared to the derived best-fit TAGB model (Figure 2).

Table 4. Allometric biomass models for crown, stem, and total above-ground biomass of *Aquilaria malaccensis*.

Model no	Model types	a	b	c	Adjusted R ²	RSE	AIC	AICw	CF
Allometric biomass models of tree crown									
1	$\text{Ln}(\text{Crown}) = a + b \cdot \text{Ln}(\text{DBH})$	-0.7273	1.2559		0.8313	0.1680	-144.7597	0.0000	1.0142
2	$\text{Ln}(\text{Crown}) = a + b \cdot \text{Ln}(\text{DBH}) + c \cdot \text{Ln}(\text{TH})$	-0.6353	0.9138	0.3719	0.8552	0.1557	-174.9899	0.3567	1.0122
3	$\text{Ln}(\text{Crown}) = a + b \cdot \text{Ln}(\text{DBH}) + c \cdot \text{Ln}(\text{WD})$	-0.7273	1.2559		0.8313	0.1680	-144.7597	0.0000	1.0142
4	$\text{Ln}(\text{Crown}) = a + b \cdot \text{Ln}(\text{DBH}^2 \cdot \text{TH})$	-0.6031	0.4279		0.8554	0.1556	-176.1694	0.6433	1.0122
5	$\text{Ln}(\text{Crown}) = a + b \cdot \text{Ln}(\text{DBH}^2 \cdot \text{WD})$	-4.3497	0.6280		0.8313	0.1680	-144.7597	0.0000	1.0142
Allometric biomass modes of stem									
1	$\text{Ln}(\text{Stem}) = a + b \cdot \text{Ln}(\text{DBH})$	-3.4432	2.5159		0.9451	0.1801	-116.3857	0.0000	1.0164
2	$\text{Ln}(\text{Stem}) = a + b \cdot \text{Ln}(\text{DBH}) + c \cdot \text{Ln}(\text{TH})$	-3.2483	1.7910	0.7881	0.9763	0.1183	-286.9550	0.5329	1.0070
3	$\text{Ln}(\text{Stem}) = a + b \cdot \text{Ln}(\text{DBH}) + c \cdot \text{Ln}(\text{WD})$	-3.4432	2.5159		0.9451	0.1801	-116.3857	0.0000	1.0164
4	$\text{Ln}(\text{Stem}) = a + b \cdot \text{Ln}(\text{DBH}^2 \cdot \text{TH})$	-3.2075	0.8588		0.9762	0.1187	-286.6914	0.4671	1.0071
5	$\text{Ln}(\text{Stem}) = a + b \cdot \text{Ln}(\text{DBH}^2 \cdot \text{WD})$	-10.6994	1.2579		0.9451	0.1801	-116.3857	0.0000	1.0164
Total above-ground biomass (TAGB) models									
1	$\text{Ln}(\text{TAGB}) = a + b \cdot \text{Ln}(\text{DBH})$	-2.0642	2.1596		0.9418	0.1595	-166.0628	0.0000	1.0128
2	$\text{Ln}(\text{TAGB}) = a + b \cdot \text{Ln}(\text{DBH}) + c \cdot \text{Ln}(\text{TH})$	-1.9121	1.5937	0.6152	0.9675	0.1192	-283.7370	0.8959	1.0071
3	$\text{Ln}(\text{TAGB}) = a + b \cdot \text{Ln}(\text{DBH}) + c \cdot \text{Ln}(\text{WD})$	-2.0642	2.1596		0.9418	0.1595	-166.0628	0.0000	1.0128
4	$\text{Ln}(\text{TAGB}) = a + b \cdot \text{Ln}(\text{DBH}^2 \cdot \text{TH})$	-1.8431	0.7349		0.9666	0.1208	-279.4310	0.1041	1.0073
5	$\text{Ln}(\text{TAGB}) = a + b \cdot \text{Ln}(\text{DBH}^2 \cdot \text{WD})$	-8.2927	1.0798		0.9418	0.1595	-166.0628	0.0000	1.0128

Table 5. Comparison of best-fit total aboveground biomass model with the various pantropical model.

Source	Equation	Type	MPE (%)	ME	RMSE
Best fit	$TAGB = \exp(-1.92107 + 1.593567 * \ln(DBH) + 0.6151991 * \ln(H))$	This study	-0.1	0.934	1109.69
Brown (1997)	$TAGB = \exp(-2.134 + 2.5430 * \ln(DBH))$	Pan-tropical	178	-15.991	17804.539
Nelson et al. (1999)	$TAGB = \exp(-1.8985 + 2.1569 * \ln(DBH) + 0.3888 * \ln(TH) + 0.7218 * \ln(WD))$	Central amazon	31	0.254	3731.814
Chave et al. (2005)	$TAGB = WD * \exp(-1.499 + 2.148 * \ln(DBH) + 0.207 * (\ln(DBH))^2 - 0.0281 * (\ln(DBH))^3)$	Pan-tropical	53	-1.124	6295.131
Brown et al. (1989)	$TAGB = \exp(-2.4090 + 0.9522 * \ln(DBH) + 2 * TH * WD))$	Pan-tropical	18	0.356	3466.618
Chave et al. (2014)	$TAGB = \exp(-2.6986 + 0.976 * \ln(DBH) + 2 * TH * WD))$	Pan-tropical	5	0.647	2566.747

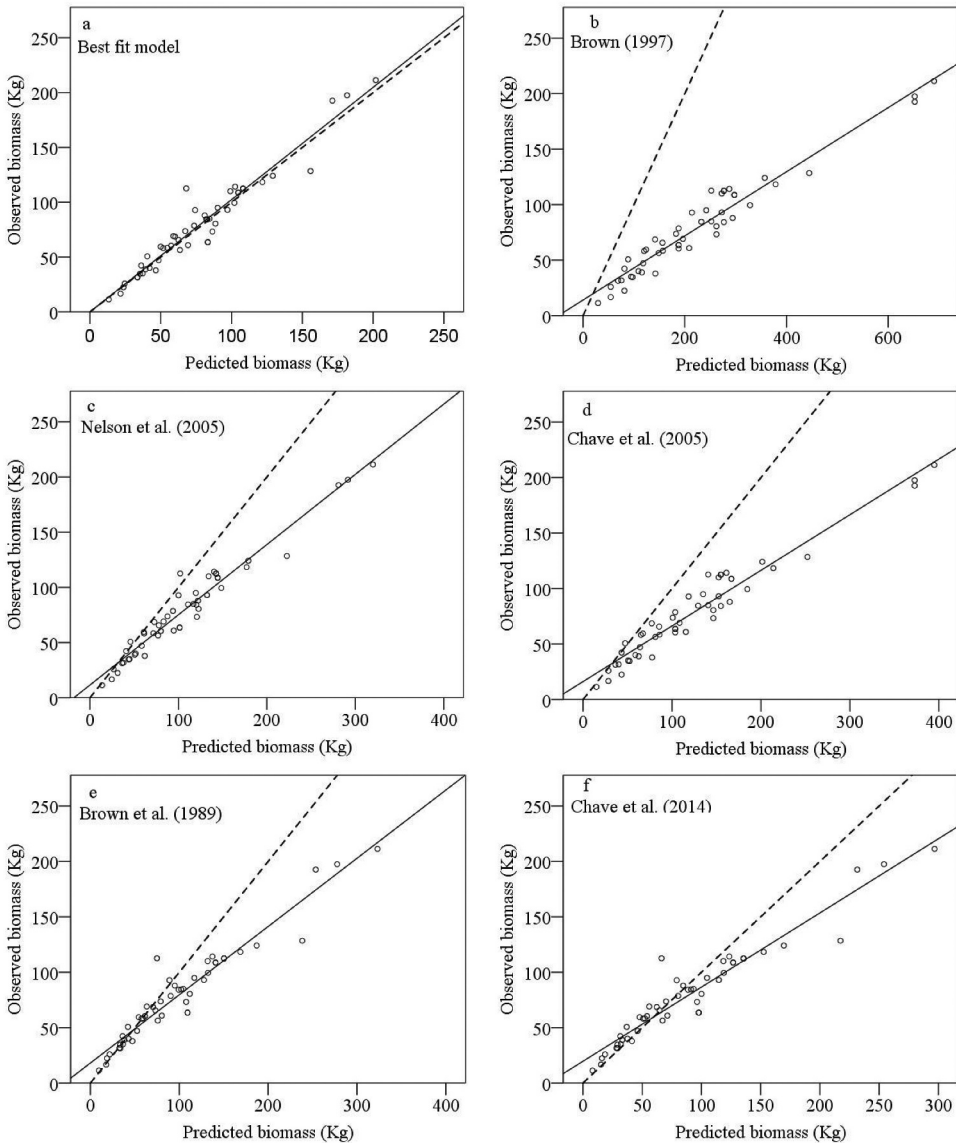


Figure 2. Comparison of best-fit total aboveground biomass model with various pantropical model.

Discussion

The development of the allometric biomass model is a laborious and time-consuming task involving field and laboratory works and precise statistical analysis (Mahmood et al., 2019; Picard et al., 2015). Allometric biomass models usually include Wood Density (WD), stem diameter (DBH), and tree height (TH) as predictor variables (Picard et al., 2015). Inclusion of WD as predictor variable along with DBH and TH is usually adopted to capture the variabilities of different tree species in a common allometric model (Chave et al., 2005; Ketterings et al., 2001). Our study showed that the inclusion of TH along with DBH increased the efficiency of model selection parameters during selecting a best-fit model

for all the components of trees like Rutishauser et al. (2013), Kusmana et al. (2018). Biomass allometric models with DBH as a single predictor variable are more convenient in the field measurement and biomass estimation (Chave et al., 2014). But, DBH as a single predictor variable of this study has shown lower efficiency for the model selection parameters. In other ways, the inclusion of WD has failed to improve the efficiency of model selection criteria (Table 4). This situation implies that a tree species from the same ecoregion would have the same wood density (Kusmana et al., 2018). Moreover, the inclusion of WD as the predicted variable is not suggested for the development of species-specific allometric models for its lower performance and robustness in use (Njana et al., 2016).

The use of regional or pantropical allometric models is still common for estimating tree biomass (Chave et al., 2014). But, the regional or pantropical allometric biomass models produce higher variation in biomass estimation compared to species-specific allometric biomass models (Ketterings et al., 2001; Ngomanda et al., 2014). Similarly, the best-fit TAGB model of *A. malaccensis* has also shown a wide variation in estimating total biomass compared to frequently used regional or pan-tropical allometric models. However, the graphical presentation of 1:1 line indicated that our best-fit TAGB model is capable to estimate total biomass more accurately than other models in comparison (Figure 2). So, it is recommended to check the range of variation in using regional or pan-tropical allometric models to estimate the biomass of trees and forests (Alvarez et al., 2012). The variation in estimated biomass may be due to the differences in tree species, climatic conditions, site conditions, forest types with its composition and management practices which ultimately influence the architecture of tree and biomass partitioning (Mugasha et al., 2016; Nam et al., 2016).

Conclusion

The inclusion of wood density as a predicted variable has not able to increase the model efficiency as this study dealt with single species. The derived allometric biomass models are capable to estimate the biomass of different components of *A. Malaccensis* at a higher accuracy compared to the frequently used regional or pan-tropical biomass models. Finally, species-specific allometric biomass models are recommended to estimate the biomass of any particular species.

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