

SEMI-DESTRUCTIVE APPROACH IN DEVELOPING ALLOMETRIC BIOMASS FOR *CHUKRASIA TABULARIS* IN SYLHET REGION OF BANGLADESH

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Species-specific biomass allometric model was crucial to measure tree biomass especially on major tree species in forests in view of their ecological and economic values. The dependent on common biomass models during forest inventory may produce inaccurate estimates since tree structure and growth varied from species and regions. In this aspect, the study aimed to derive the best-fit allometric model to estimate aboveground biomass of *Chukrasia tabularis* in Sylhet Region of Bangladesh. A semi destructive method where total height (H), diameter at breast height (D) and wood density were used as independent variables to check the efficiency of the commonly used pan-tropical models in biomass estimation of the species. A total of 120 individual trees were purposively selected for model development and validation. Ten regression equations were tested in the study for biomass allometric model and seven for predicting height-diameter at breast height relationship. The best-fit model was selected based on adjusted R², residual standard error, the Akaike information criterion and Akaike weights. Finally, the derived model was compared with the commonly used pan-tropical biomass models in terms of model efficiency and root mean square error. The best-fitted biomass allometric model for *C. tabularis* was $\text{Ln}(\text{TAGB}) = -3.571 + 1.006 \times \text{Ln}(D^2 \times H)$. The derived best-fit model showed higher efficiency in biomass estimation compared to the commonly used pan-tropical models.

Keywords: Allometry, above-ground biomass, biomass estimation method, species-specific model, tropical forest.

INTRODUCTION

Deforestation and forest degradation caused by different landuse systems accounted for about 25% of global carbon emissions over the period 1870–2014 (Le Quéré et al. 2014). In recent years, various initiatives such as REDD⁺ were practiced to reduce global carbon emission and enhance carbon sequestration in forests (Alexander 2018). Nevertheless, proper implementation of those initiatives required authentic ground-based monitoring of global carbon storage (Fearnside 2012, Tulyasuwan et al. 2012). Presently, carbon monitoring is widely used based on remote-sensing and GIS techniques and observed in many recent studies (Arıcak et al. 2015, Bindu et al. 2018). Nevertheless, their calibrations required accurate ground-based biomass and carbon storage estimation (Asner et al. 2010, Saatchi et al. 2011, Clark & Kellner 2012). Biomass estimation was directly related to the

studies of carbon sequestration and assisted in conducting forest inventory and strengthens sustainable management (Picard et al. 2012).

Allometric model was commonly used to measure tree biomass by taking the tree biometric measurements (Brown 1997). However, there were uncertainties regarding the quality of these allometric models in assessing aboveground biomass (Chave et al. 2014, Clark & Kellner 2012, Sileshi 2014). Appropriate model selection has significant effect on the accuracy of biomass stock measurement. Moreover, tree species posed considerable impacts on both ecology and economy. A good species-specific biomass allometric model, would enable proper management of the selected area (Mahmood et al. 2019a). Biomass allometric models basically referred to mathematical functions by which the relationship between tree biomass with

tree diameter at breast height or wood density were represented for a distinct species or a community (Ketterings et al. 2001, Sileshi 2014). The inclusion of more variables such as tree height in biomass allometric models generally yielded less biased estimates (Chave et al. 2005). In the tropics, pan-tropical biomass allometric models were suggested by Chave et al. (2005) and commonly used for biomass estimation of trees (Nam et al. 2016). In many instances, these models produced less accurate estimates compared to the species-specific and site-specific models due to the spatial variability (Van Breugel et al. 2011). Therefore, species-specific and site-specific biomass allometric models were preferred over the use of common models (Mahmood et al. 2015).

Destructive method for developing allometric model is the most accurate for biomass estimation, but it requires time and intensive labour to increase the sample areas and sample sizes. (Ketterings et al. 2001, Deb et al. 2012). The development of allometric models using non-destructive technique is sometimes limited to stem biomass. In this aspect, the semi-destructive approach offers a solution in the development of allometric biomass model and can easily be conducted in reserved areas (Picard et al. 2012, Mahmood et al. 2020).

Chukrasia tabularis is a tropical hill forest tree species. It is distributed from India to Indonesia (Kalinganire & Pinyopusarek 2000). In Bangladesh, this species is mostly found in Sylhet region. Presently, *C. tabularis* needed special attention for its various applications including high-valued commercial use. There are 222 validated allometric volume and biomass allometric models in Bangladesh but only a small area of forest trees species are included (Mahmood et al. 2019b). In a recent study by Mahmood et al. (2019b), 14 hill forest tree species were considered in order to derive a common allometric model for the estimation of tree above ground biomass in the hill region of Bangladesh. However, *C. tabularis* being one of the most significant hill forest tree species was not included and had not been studied. With this regard, the study aimed to derive the relationship between total height and diameter at breast height of *C. tabularis*, to develop a related species-specific allometric biomass model and to check the efficiency of the commonly used pan-tropical models in biomass estimation of this species.

MATERIALS AND METHODS

Study area

The study was conducted in Rema-Kalenga Wildlife Sanctuary (24° 06'–24° 14' N and 91° 35'–91° 40' E) (Figure 1). It is the largest upland wildlife sanctuary in Bangladesh, which falls under Habiganj Forest Range-2 in Sylhet Forest Division. The study area has tropical moist climate and a characteristics high rainfall from May to August (Holdridge 1967, Islam et al. 2018). The annual average rainfall and temperature are 2363 mm and 24.8 °C respectively over the period 1950–2015 (Islam et al. 2018). The soil texture of the study area varies from clay loams on level ground to sandy loams on hilly ground (Hassan 1994). The study site has dominating plant species such as *Chukrasia tabularis*, *Dipterocarpus turbinatus*, *Tectona grandis*, *Toona ciliata*, *Syzygium grandis*, *Lagerstroemia speciosa* and different species of *Albizia* (Islam et al. 2018).

Sampling and measurement of sample trees

A total of 120 *C. tabularis* individual trees were selected purposively from the study area. Trees with broken top, damaged, hollow trunk and evidence of suppression or disease were discarded during the selection. In the first event, 98 individuals were chosen to derive the allometric model, covering diameter at breast height and total height range of 9–52 cm and 9–37 m respectively. Seven diameter classes were taken to cover the diameter at breast height range starting from 9.0–15.1 cm, 15.1–21.2 cm, 21.2–27.3 cm, 27.3–33.4 cm, 33.4–39.5 cm, 39.5–45.6 cm and 45.6–51.7 cm. Fourteen individuals were selected from each classes. In the second event, 22 individuals were selected from those classes for model validation and evaluation. Diameter at breast height and total height of the trees were measured and recorded. Sectional volume of tree stem and the bigger branches (diameter > 7 cm) of the sampled trees were measured using semi-destructive method as described in Mahmood et al. (2016). The base diameters of all small branches (diameter ≤ 7 cm) of each sample tree were measured by climbing on to the tree. A total of 30 smaller branches were trimmed from different trees at base and their base diameters were recorded separately.

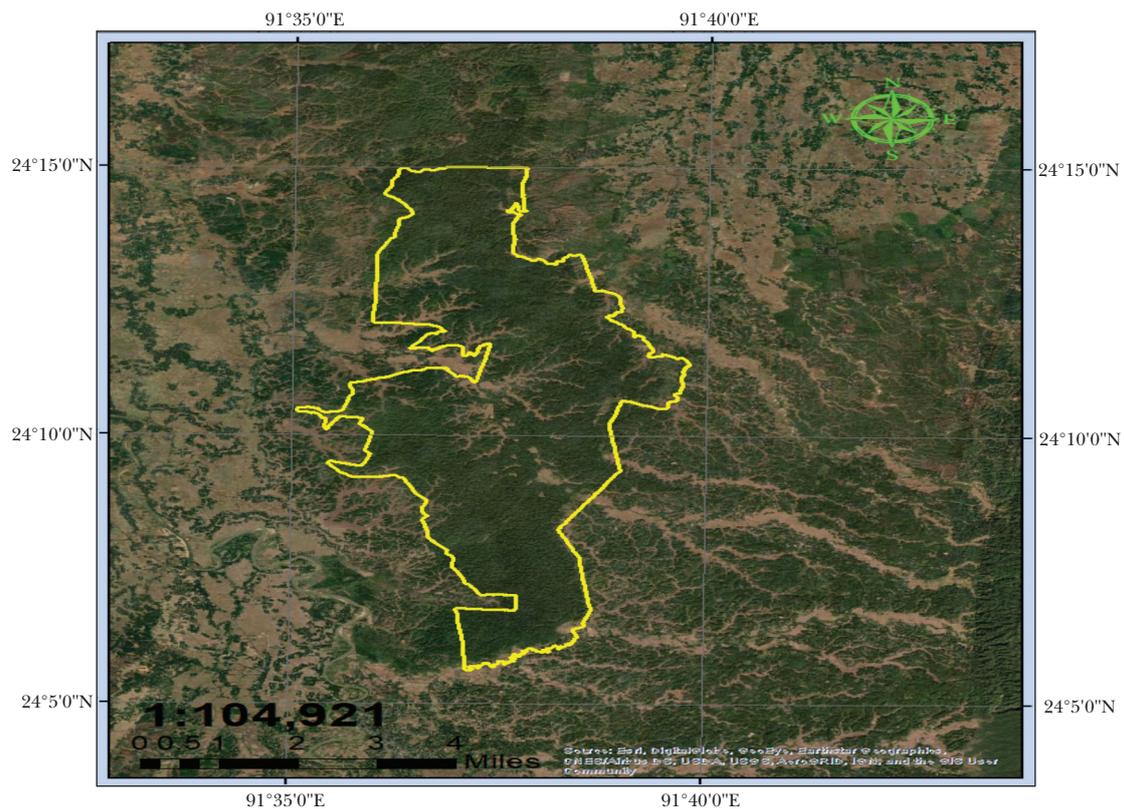


Figure 1 Location of the study site

Wood density measurement

As logging is banned in reserved forest, an individual *C. tabularis* was felled from the outside the forest for wood density estimation. One representative stem disc about 7.5 cm thick was taken from the base, middle and top portion of the sampled tree. Six sub-samples of wood (2.5 cm × 2.5 cm × 7.5 cm) were collected from each disk at 2 cm interval from periphery to the centre of disk. The wood samples were oven dried at 105 °C until constant weight was achieved and the weight of the oven-dried samples were measured by using high-precision digital laboratory balance. Volume of the samples was measured using water displacement method (Picard et al. 2012, Mahmood et al. 2016). Finally, the wood density of *C. tabularis* was derived using equation (1).

$$\text{Wood density (kg m}^{-3}\text{)} = \frac{\text{Oven-dry weight of sample (kg)}}{\text{Fresh volume of the sample (m}^3\text{)}} \quad (1)$$

Height-diameter at breast height relationship of *C. tabularis*

A total of seven models ($H = a + b (D)$, $H = a + b (1/D)$, $1/H = a + b (1/D)$, $H = a + b \ln (D)$, $\ln (H) = a + b (1/D)$, $\ln (1/H) = a + b (D)$ and $\ln (H) = a + b \ln (D)$) were used to derive the height-diameter at breast height relationships (Parresol 1992, Vanclay 1995, Mahmood et al. 2019c). The model which showed the lowest residual standard error (RSE) and the highest coefficient of determination (adjusted R^2) was selected as the best fit model (Picard et al. 2012).

Development of branch allometry

The trimmed small branches were separated into leaves, leaves containing smaller branches and woody part. The fresh weight of each part was measured in the field using a portable digital balance. Thirty sub-samples (about 250 g each) from each part were collected and put into air tight zip-polybag to avoid rapid moisture loss. The collected samples were taken immediately

to the laboratory, where conversion ratio of fresh to oven-dry weight was derived at 70 °C. The conversion ratio of respective parts were multiplied with the fresh weight of branch parts to get oven-dry weight of branch parts (Mahmood et al. 2019c).

Base diameter of smaller branches and biomass of branch components (leaf, leaf containing smaller branch and woody parts of branch) were considered as predictor and output variables respectively. These variables were transformed into natural logarithm (Ln) to derive the branch allometric biomass models. Models having highest adjusted R² value and lowest residual standard error (RSE) as well as AIC value were selected as best fit model (Mahmood et al. 2019c). For bias minimisation of Ln transformed equations, a correction factor (CF) was calculated (Sprugel 1983). The developed branch allometry model was used to enumerate the biomass of the smaller branches (diameter ≤ 7 cm) of the trees.

Biomass of stem and bigger branches

Sectional volume of stem and bigger branches were measured using the Newton’s formula as in equation 2 (Cruz de León & Uranga-Valencia 2013).

$$V = \frac{S_1 + 4S_m + S_2}{6} \times L \tag{2}$$

where, V is the volume of the section, S₁ is the cross-sectional area at the large end, S_m is the

cross-sectional area at the middle, S₂ is the cross-sectional area at the small end and L is length of the section.

Finally, stem and bigger branch biomass were enumerated using equation 3 (Mahmood et al. 2016).

$$\text{Biomass} = \text{Volume (m}^3\text{)} \times \text{Wood density (kg m}^{-3}\text{)} \tag{3}$$

Allometric biomass models for total above ground biomass

Total above ground biomass (TAGB) was calculated by adding the biomass of stem, bigger branches and smaller branches. Total height and diameter at breast height were considered as predictor variables and biomass as response variable. Ten frequently used equations, as shown in Table 1, were tested to derive the best-fit allometric biomass (Brown et al. 1997, Nelson et al. 1999, Deb et al. 2012, Mahmood et al. 2019b).

The model having the lowest Akaike Information Criterion (AIC) and Residual Standard Error (RSE), and the highest Akaike Information Criterion weight (AICw) and adjusted R² values was selected as best fit model. However, models having RSE value greater than 0.30 were discarded and not allowed for further validation and comparison (Picard et al. 2012, Sileshi 2014, Mahmood et al. 2019a). In addition, Durbin-Watson (D-value) test was conducted to check autocorrelation in the error

Table 1 Functions tested for developing allometric model

Model no	Equation	Type
1	TAGB = a + b × (D)	Linear
2	TAGB = a + b × (D) + c × (D × H)	Linear
3	TAGB = a + b × (D ² × H)	Linear
4	Ln (TAGB) = a + b × Ln (D)	Log-linear
5	Ln (TAGB) = a + b × Ln (H)	Log-linear
6	Ln (TAGB) = a + b × Ln (D × H)	Log-linear
7	Ln (TAGB) = a + b × Ln (D ² × H)	Log-linear
8	Ln (TAGB) = a + b × Ln (D) + Ln (H)	Log-linear
9	Ln (TAGB) = a + b × Ln (D ²)	Log-linear
10	Ln (TAGB) = a + b × Ln (D ²) + c × Ln (D ² × H)	Log-linear

Ln = natural Log, TAGB = total above ground biomass, D = diameter at breast height, H = total height of the tree

terms (Robinson & Hamann 2010, Picard et al. 2012). Multicollinearity among the predictors in a model was checked using variance influential factor (VIF), where the test results of $VIF > 5$ indicated the existence of multicollinearity (Sileshi 2014). Shapiro-Wilk (SW) test was conducted to check the normality of residuals of the models. Finally, a correction factor (CF) was calculated for bias minimization of Ln transformed equation (Sprugel 1983).

Model validation

The selected best-fit total above ground biomass (TAGB) model was validated and compared with the commonly used pan-tropical biomass models of Brown (1997) and Chave et al. (2005) using the data set of the second event in terms of model efficiency (ME) and root mean square error percentage. Model efficiency was calculated using equation 4. Model efficiency value close to 1 was regarded as near perfect (Mayer & Butler 1993).

$$\text{Model efficiency} = 1 - \left[\frac{\sum(Y_o - Y_p)^2}{\sum(Y_o - \bar{Y})^2} \right] \quad (4)$$

where, Y_p is the predicted biomass from model; Y_o is the observed biomass in field measurement and \bar{Y} is the mean of the observed biomass.

Observed biomass and predicted biomass were regressed, where Y_p was kept in the X-axis and Y_o in the Y-axis. It helped to compare the best-fit model with the pan-tropical models. Significance of slope ($b = 1$) and intercept ($a = 0$) were also tested to understand the overestimation or underestimation of the predicted biomass

of each model from 1:1 line (Piñeiro et al. 2008, Sileshi 2014). Every statistical analysis was conducted using R (3.5.2) software. The alpha level for all statistical analysis was 0.05.

RESULTS

Wood density and height-diameter at breast height relationship

Wood density of *C. tabularis* was found varying between 0.44 and 0.64 g cm⁻³ while the average was 0.55 g cm⁻³ with a standard deviation of 0.06. The linear model ($1/H = 0.024 + 0.643 \times (1/D)$) appeared as best-fit model for total height and diameter at breast height relationship with the highest adjusted R² value (0.617) and lowest RSE value (0.011) showed in Table 2.

Allometric models for the smaller branches

The best-fit models for leaf, leaf containing smaller branches (LCSB), woody parts of smaller branches (WSB) and total biomass of smaller branches were leaf = $-0.25 + 0.196 \times$ base diameter, LCSB = $-0.245 + 0.139 \times$ base diameter, Ln (WSB) = $-2.945 + 2.097 \times$ Ln (base diameter and Ln (branch biomass) = $-2.111 + 1.926 \times$ Ln (base diameter)) respectively (Table 3).

Allometric models for total aboveground biomass

The linear models tested in the study showed higher RSE and AIC value. Model 7 (Ln (TAGB) = $-3.571 + 1.006 \times$ Ln ($D^2 \times H$)) showed the lowest AIC value (4.893) and RSE value (0.243) and

Table 2 Estimated parameters of different models to derive height (H) and diameter at breast height (D) relationship

Model no.	Equation	a	b	Adj. R ²	RSE
1	H = a + b (D)	13.257	0.273	0.260	5.566
2	H = a + b (1/D)	29.341	-189.418	0.424	4.909
3	1/H = a + b (1/D)	0.024	0.643	0.617	0.011
4	H = a + b Ln (D)	-5.708	8.238	0.359	5.178
5	Ln (H) = a + b (1/D)	3.462	-10.659	0.544	0.217
6	Ln (1/H) = a + b (D)	-2.553	-0.015	0.340	0.262
7	Ln (H) = a + b Ln (D)	1.491	0.463	0.460	0.236

Ln = natural Log, RSE = residual standard error

Table 3 Allometric model for smaller branches

Equation	a	b	Adj. R ²	RSE	AIC	CF
Leaf = a + b × (base diameter)	-0.250	0.196	0.626	0.206	-5.691	
Ln (Leaf) = a + b × Ln (base diameter)	-3.075	1.680	0.658	0.375	30.320	1.073
LCSB = a + b × (base diameter)	-0.245	0.139	0.541	0.172	-16.280	
Ln (LCSB) = a + b × Ln (base diameter)	-4.107	1.974	0.575	0.524	50.344	1.147
WSB = a + b × (base diameter)	-1.271	0.592	0.779	0.429	38.346	
Ln (WSB) = a + b × Ln (base diameter)	-2.945	2.097	0.871	0.251	6.339	1.032
Branch biomass = a + b × (base diameter)	-1.768	0.928	0.797	0.638	62.144	
Ln (Branch biomass) = a + b × Ln (base diameter)	-2.111	1.926	0.871	0.231	1.326	1.027

Ln = natural Log, LCSB = leaf containing smaller branches, WSB = woody parts of smaller branches, RSE = residual standard error, AIC = Akaike Information Criterion, CF = correction factor

highest adjusted R² value (0.960) and AICw value (0.540) (Table 4).

Model 8 appeared as the closest candidate to model 7 but it was found to have higher AIC value (6.601) and lower AICw value (0.230). Finally, the back transformed model was:

$$\begin{aligned} \text{Ln (TAGB)} &= -3.571 + 1.006 \times \text{Ln (D}^2 \times \text{H)} \text{ or} \\ \text{TAGB} &= \exp (-3.571 + 1.006 \times \text{Ln (D}^2 \times \text{H)}) \text{ or} \\ \text{TAGB} &= 0.028953 \times (\text{D}^2 \times \text{H})^{1.006} \end{aligned}$$

Hence, the bias corrected model was
 $= 1.029 \times 0.028953 \times (\text{D}^2 \times \text{H})^{1.006}$
 $= 0.029821 \times (\text{D}^2 \times \text{H})^{1.006}$

Model validation

The best-fit model 7 showed the highest model efficiency value (0.972) and the lowest root mean square error value (13.119) compared to the commonly used regional and pan-tropical above ground biomass allometric models.

After comparing the observed against the predicted biomass, deviation was observed in biomass estimation from the line of significance of slope (b = 1) and intercept (a = 0) shown in Figure 2. It indicated that biomass allometric model of Chave et al. (2005) and Brown (1997) overestimated the biomass of the sample tree.

DISCUSSION

The appropriate selection of allometric models provided accuracy in biomass estimation of species (Nam et al. 2016). Careful investigation of model parameters was necessary in model

selection (Sileshi 2014). Moreover, accurate measurements of independent variables such as tree height and diameter at breast height increased model acceptability and applicability (Overman et al. 1994). Addition of more variables such as wood density in biomass estimation model improved the validity of the model (Brown et al. 1989) and could be used as predictor variable in multi-species biomass model (Ebuy et al. 2011, Mahmood et al. 2019b) Wood density played a greater role as independent variable in biomass model for mixed species (Basuki et al. 2009). Many studies did not include wood density as predictor in species-specific allometric biomass model (Abich et al. 2019). Nevertheless, the study derived the mean wood density of *C. tabularis* which was quite similar with the local database of Sattar (1999).

The study covered a wide range of diameter at breast height (9–52 cm) and total height (9–37 m) of tree, which added confidence to the model validity. The log transformed model performed better for small branch biomass, which was in line with Mahmood et al. (2019b,c). Model 7 was selected as the best-fit model. In addition, the bias corrected model ($\text{TAGB} = 0.029821 \times (\text{D}^2 \times \text{H})^{1.006}$) was given for easier estimation of biomass. However, both models 6 and 8 showed statistical credibility as per the selection criteria (Sileshi 2014).

The best-fitted total aboveground biomass model developed in this study had the trend to over-estimate the biomass with increased diameter at breast height, which was evident in Figure 2. However, it showed higher model efficiency (0.972) compared to the commonly

Table 4 Estimated parameters of different linear models tested in the study

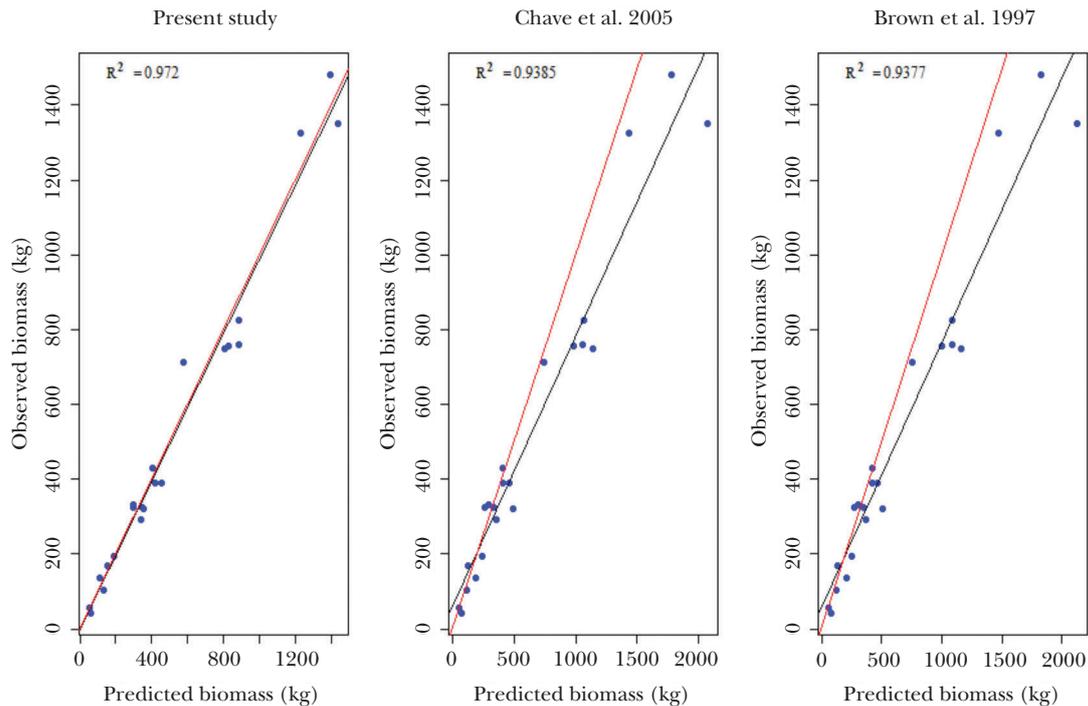
Model no.	a	b	c	Adjusted R ²	RSE	AIC	AICw	D value	SW test	P value of SW test	CF	VIF
1	-561.937	43.861		0.786	278.6	1385.533	0.000	2.136	0.839	***		
2	-478.413	25.121	0.700	0.817	257.8	1371.293	0.000	2.263	0.846	***		a = 5.47, b = 5.47
3	11.457	0.030		0.835	244.5	1359.929	0.000	2.352	0.803	***		
4	-2.089	2.483		0.927	0.331	65.458	0.000	1.291	0.991	0.80	1.056	
5	-3.003	3.0080		0.622	0.753	226.559	0.000	0.553	0.957	***	1.328	
6	-4.137	1.620		0.942	0.294	42.707	0.000	1.389	0.980	0.15	1.044	
7	-3.571	1.006		0.960	0.243	4.893	0.540	1.638	0.981	0.18	1.029	
8	-3.507	2.043	0.951	0.960	0.244	6.601	0.230	1.635	0.983	0.24	1.030	a = 1.87, b = 1.87
9	-2.089	1.241		0.927	0.331	65.45	0.000	1.291	0.991	0.80	1.056	
10	-3.507	0.070	0.951	0.960	0.244	6.601	0.230	1.635	0.983	0.24	1.030	a = 25.7, b = 25.7

RSE = residual standard error, AIC = Akaike Information Criterion, AICw = Akaike Information Criterion weight, CF = correction factor, VIF = Variance Influential Factor, D = Durbin-Watson test, SW = Shapiro-Wilk test; *** = significance codes 0

Table 5 Comparison among the best fit models with the commonly used biomass allometric model

Source	Equation	Type	ME	RMSE %
Present study	$\text{Ln (TAGB)} = -3.571 + 1.006 \times \text{Ln (D}^2 \times \text{H)}$	Species-specific	0.972	13.119
Chave et al. (2005)	$\text{TAGB} = \text{WD} \times \exp (-1.499 + 2.148 \times \text{Ln (D)} + 0.207 \times (\text{Ln(D)})^2 - 0.028 \times (\text{Ln (D)})^3)$	Pan-tropical	0.702	43.134
Brown (1997)	$\text{TAGB} = \exp (-2.134 + 2.543 \times \text{Ln (D)})$	Pan-tropical	0.655	46.376

Ln = natural Log, TAGB = total above ground biomass, D = diameter at breast height, H = total height of the tree, ME = model efficiency, RMSE = root mean square error



The black line is the regression line, and the red line is the significance of slope ($b = 1$) and intercept ($a = 0$)

Figure 2 Regression analysis between observed and predicted values

used biomass allometric model of Brown (1997) and Chave et al. (2005) (Table 5). It showed the less efficiency of the common pan-tropical models in predicting biomass of this particular species. Significant deviations were found in those models due to inclusion of only diameter at breast height in biomass model (Nam et al. 2016). It was also found that in several previous studies, the use of common pan-tropical biomass estimation model generated more uncertainty than locally developed models (Maulana et al. 2016, Mahmood et al. 2020). The uncertainty was generally caused geographical positions, environmental factors, site condition and tree structure (Van Breugel et al. 2011, Nam et al. 2016).

The semi or non-destructive method was not very accurate and precise compared to the destructive method. There were sources of uncertainty related to biomass calculation using tree volume model, form factor, wood density and biomass expansion factor. About 10 to 16% of overestimation in biomass was expected at the stand level compared to the destructive method as stated by Njana (2017). In addition, significant error in the calculation might arise for larger trees with hollow trunk. Besides, using

allometric equations in biomass estimation may result in small to very large percentage of error (Araújo et al. 1999). However, the study avoided such abnormalities of trees when higher model efficiency was found in the derived model compared to other pan-tropical models. Hence, the study had confidence of semi-destructive method in species-specific biomass estimation of tropical tree species (Mahmood et al. 2019c). Further studies are required to explore other factor of uncertainties in this method for mixed or specific species in the tropics.

The derived model for *C. tabularis* in the study was suggested to be applied for forest inventory in the tropics. It may also assist in the ground calibration of aboveground biomass estimation using remote sensing technique. However, the study was carried out based on a regional context and limited to the given range of diameter at breast height and total height of trees. Nevertheless, comprehensive and representative data were required to find a suitable model at national or global scale. In future studies, the procedure can be replicated to derive species-specific local allometric biomass model for other tree species.

CONCLUSION

The semi-destructive method in developing allometric model for biomass estimation is gaining growing popularity due to its high degree of precision and easy applicability in forests. The study estimated the mean wood density of *C. tabularis* separately to provide a site-specific value and the height-diameter at breast height relationship to generate further understanding about the species. The derived corrected best-fit model ($TAGB = 0.029821 \times (D^2 \times H)^{1.006}$) on *C. tabularis* in the study performed better than the commonly used pan-tropical biomass models in tropics. The findings of the study will contribute significantly to the future management and sustainable logging operation of *C. tabularis* in designated forest.

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