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ORIGINAL PAPER

Applicability of semi-destructive method to derive allometric model for estimating aboveground biomass and carbon stock in the Hill zone of Bangladesh

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Abstract Biomass estimation using allometric models is a nondestructive and popular method. Selection of an allometric model can influence the accuracy of biomass estimation. Bangladesh Forest Department initiated a nationwide forest inventory to assess biomass and carbon stocks in trees and forests. The relationship between carbon storage and sequestration in a forest has implications for climate change mitigation in terms of the carbon sink in Bangladesh. As part of the national forest inventory, we aimed to derive multi-species biomass models for the hill zone of Bangladesh and to determine the carbon concentration in tree components (leaves, branches, bark and stem). In total, 175 trees of 14 species were sampled and a semi-destructive method was used to develop a biomass model, which included development of smaller branch (base dia < 7 cm) biomass allometry and volume estimation of bigger branches and stems. The best model of leaf, branches, and bark showed lower values for adjusted R^2 (0.3152–0.8043) and model efficiency (0.436–0.643), hence these models were not recommended to estimate biomass. The best fit model of stem and total aboveground biomass (TAGB) showed higher model efficiency 0.948 and 0.837, respectively, and this model was recommended for estimation of tree biomass for the hill zone of Bangladesh. The best fit allometric biomass model for stem was Ln (Stem) = − 10.7248 + 1.6094*Ln (D) + 1.323*Ln (H) + 1.1469*Ln (W); the best fit model for TAGB was Ln (TAGB) = − 6.6937 + 0.809*Ln (D^2*H*W), where DBH = Diameter at Breast Height, H = Total Height, W = Wood density. The two most frequently used pan-tropical biomass models showed lower model efficiency (0.667 to 0.697) compared to our derived TAGB model. The best fit TAGB model proved applicable for accurate estimation of TAGB for the hill zone of Bangladesh. Carbon concentration varied significantly ($p < 0.05$) by species and tree components. Higher concentration (48–49%) of carbon was recorded in the tree stem.

Keywords Allometry · Bangladesh · Biomass · Carbon · Forest inventory

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Introduction

Forests of Bangladesh have been classified as tropical evergreen or semi evergreen forest, tropical moist or dry deciduous forests and tidal mangrove forest, all of which have been managed scientifically for over 100 years. Twenty-six inventories have been conducted for the forests of Bangladesh at regional and national scales. The objectives of these inventories shifted from volume estimation to biomass and carbon stock assessment (FD 2017a). Timber volume stock was assessed using species specific volume tables or volume equations (Mahmood et al. 2016a). Biomass estimation during the first National Forest and Tree Resources Assessment; and carbon inventory for the Sundarbans and eight protected areas were highly dependent on generalized and species-specific volume equations, and pantropical biomass models (FD 2007; Donato et al. 2011; Latif et al. 2015). The use of such allometric models can reduce accuracy in biomass and carbon stock assessment (Maulana et al. 2016; Nam et al. 2016).

The second National Forest Inventory was underway in Bangladesh in 2018 with the objectives of accurate assessment of biomass and carbon stock in trees and forests (FD 2017b). This inventory has stratified the trees and forests into hill, sal, sundarbans, coastal and village zone based on climatic and geophysical properties (Akhter et al. 2016). Localized, multi-species allometric biomass models are expected to be developed for each of these zones. Allometric technique is a semi- or non-destructive method of tree biomass estimation (Golley et al. 1975; Picard et al. 2012), where mathematical functions are derived to relate tree biomass with easily measurable biometrical predictors such as diameter at breast height (DBH), height (H) and wood density (W) (Sileshi 2014). Allometric equations can be developed for individual species or to represent a community at local, regional or biospheric (pan-tropical) scales. Species-specific and site-specific multi-species biomass allometric models can ensure desired accuracy in biomass estimation (Ketterings et al. 2001; Manuri et al. 2014; Maulana et al. 2016). Bangladesh has 222 validated allometric volume and biomass allometric models. But, the hill zone has only 10 allometric biomass models for three species (*Senna siamea* (Lam.) Irwin et Barneby, *Artocarpus chaplasha* Roxb. and *Tectona grandis* L.f. (Mahmood et al. 2016a), while this zone contains at least 47 tree species both in natural stands and in plantations (Nur et al. 2016). Development of species-specific allometric biomass models for tree species of this zone would be time consuming and labour intensive if based on destructive sampling (felling of trees). As part of the current National Forest Inventory, the aim of this study was to derive multi-species allometric biomass models for the frequently occurring tree species of the hill zone of Bangladesh.

Materials and methods

Study area

The hill zone of Bangladesh is located in the northeast and southeast corners of Bangladesh and covers about 17,174 Km^2 of land area (Fig. 1). This zone consists of tropical evergreen and semi-evergreen vegetation with natural and plantation stands. The major naturally occurring tree species are *A. chaplasha*, *Albizzia* spp., *Dipterocarpus* spp., *Duabanga grandiflora* (Roxb. ex DC.) Walpers, *Gmelina arborea* Roxb., *Hopea odorata* Roxb., *Lagerstroemia speciosa* (L.) Pers., *Mangifera sylvatica* Roxb., *Swintonia floribunda* Griff., *Syzigium* spp., *Toona ciliata* M. Roem. (FD 2017c). The soil of this zone is yellowish brown to reddish brown in colour, loam to clay loam and sandy clay loam. Soil is acidic and organic matter content of the topsoil varies from 0.15 to 3.32%. While, total nitrogen concentration varies from 0.03 to 0.24%. The ranges of available form of soil phosphorus, potassium, calcium, and magnesium are 1.38 to 7.32 mg kg^{-1}, 62 to 206 mg kg^{-1}, 279 to 928 mg kg^{-1}, and 74 to 371 mg kg^{-1}, respectively (Hossain et al. 2014).

Sampling of tree species

A total of 175 individuals of 14 tree species representing 11 families (Table 1) were collected during two sessions from 50 sample plots of 19 m radius that covered a wide range of DBH and total height classes. All sample trees were selected to avoid specimens with broken top, hollow trunk, damage caused by natural calamities or animals, and evidence of suppression or disease. We collected 136 individuals during the first event (Table S1 Biomass Data Set A, Supplementary data), which was used to derive the allometric models. While, the remaining 39 individuals were collected during the second event (Table S2 Biomass Data Set B, Supplementary data) and that was used for validation and evaluation of the derived allometric models.

Field measurement and laboratory analysis

Total height and DBH of sampled trees were measured. A non-destructive method was used to estimate the volume of stems and larger branches (diameter > 7 cm). Base diameter of all small branches (diameter < 7 cm) of the sampled trees were measured and 2 to 3 smaller branches were trimmed from each sampled tree. These trimmed branches were separated into components (leaves, leaf containing smaller branch, and woody parts of branch) to measure their fresh biomass in the field.

Ten sub-samples (about 0.25 kg) of each component (leaves, leaf containing smaller branch, and woody parts of branch) of trimmed branches of each species were collected from the field. These were oven-dried at 105 °C to constant weight to derive a fresh to oven-dried weight conversion ratio (Mahmood et al. 2015). Wood samples of bigger branches and stems of sampled species were collected using battery powered hand drill. Carbon

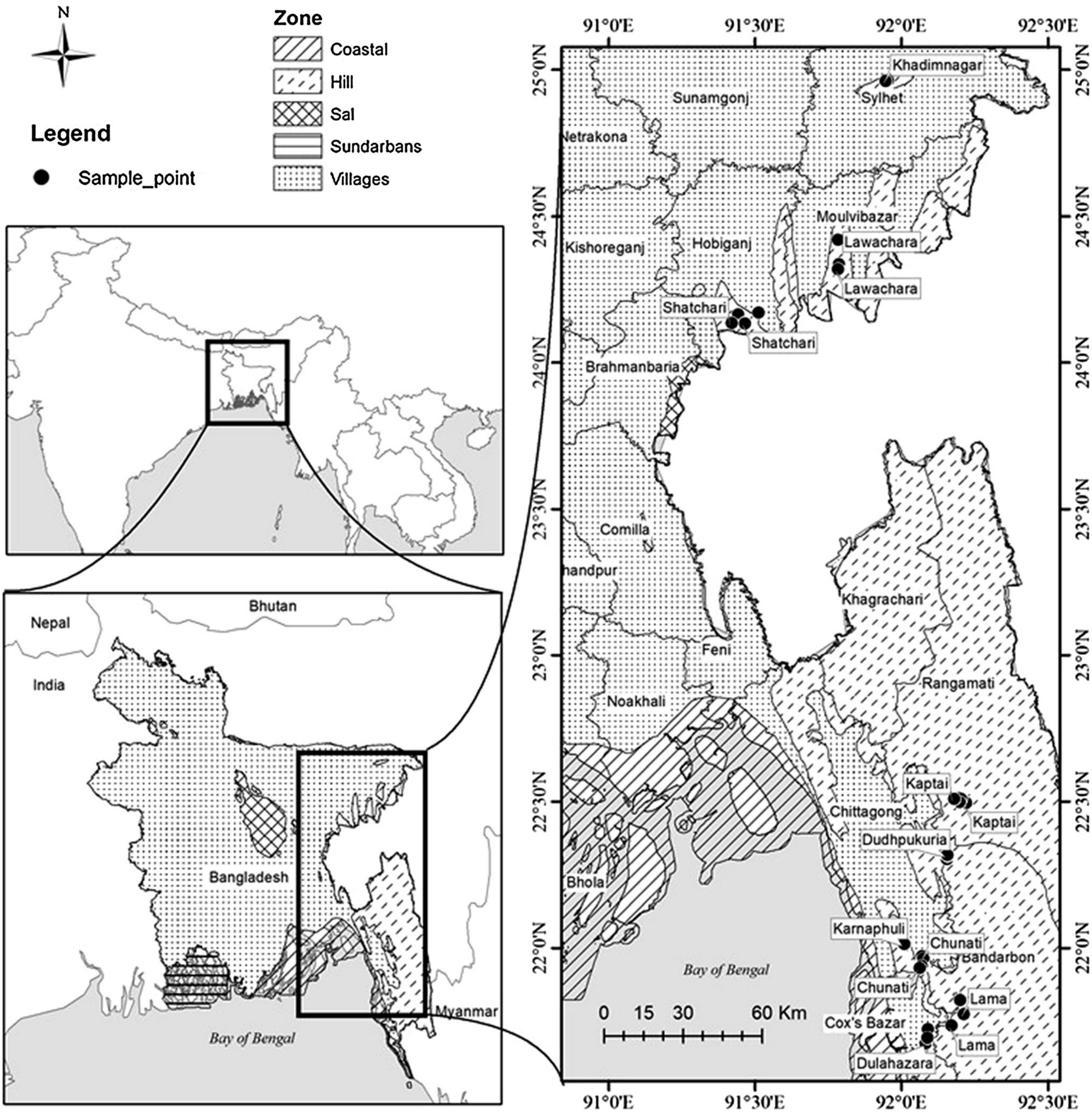

Fig. 1 Forest zones of Bangladesh and sample collection sites

concentration of components (leaf, smaller branches, bigger branches and stem) were measured by use of the ignition loss method (Allen 1989). Carbon concentration were compared by two-way analysis of variance using R (3.2.3) statistical software.

Allometric biomass models for the smaller branches

Base diameter of branches and biomass of branch components (leaf, leaf containing smaller branch (LCB), and woody parts of branch) were considered as predictor and output variables respectively. These variables were Ln (natural logarithm) transformed to derived the species-specific branch allometric biomass models (Ln (biomass) = $a + b$ Ln (base diameter of branch)) using R (3.2.3) statistical software. A correction factor (CF) was calculated for each equation to minimize the systematic bias during the back transformation of Ln values to biomass values (Sprugel 1983).

Table 1 Species used to develop the common allometric equation for the Hill zone of Bangladesh with number of observation and wood density value. Wood density *Source*: Zanne et al. (2009)

Species	Family	Wood density (kg m^{-3})
Albizia spp.	Fabaceae	571
Aquilaria malaccensis	Thymelaeaceae	320
Artocarpus chaplasha	Moraceae	459
Dipterocarpus turbinatus	Dipterocarpaceae	619
Eucalyptus camaldulensis	Myrtaceae	721
Hevea brasiliensis	Euphorbiaceae	492
Hopea odorata	Dipterocarpaceae	635
Lagerstroemia speciose	Lythraceae	595
Senna siamea	Caesalpiniaceae	660
Swietenia mahagoni	Meliaceae	630
Syzygium grande	Myrtaceae	673
Tectona grandis	Verbenaceae	720
Terminalia arjuna	*Combretaceae*	822
Terminalia bellirica	*Combretaceae*	760

Biomass of sampled tree

Oven-dry biomass of stem and larger branches was estimated from their calculated volume (m^3) and the mean wood density (Kg m^{-3}) of the respective tree species. Mean wood densities were used from the data base of Zanne et al. (2009) (Table 1) and these values were compared by one-way analysis of variance using R (3.2.3) statistical software. Oven-dry biomass of smaller branches of the individual sampled trees was estimated from the derived species-specific branch allometric model and oven-dry biomass of trimmed branches of the sampled trees (Picard et al. 2012).

Allometric models for tree components and total above-ground biomass (TAGB)

DBH, tree height, and wood density were designated as predictor variables while biomass of leaf, branch, bark, stem and TAGB were designated as output variables. All variables were Ln (natural logarithm) transformed to improve linearity and homoscedasticity (Zar 1996). A total of eight allometric models (Table 2) were tested to derive the allometric model for the output variables using R (3.2.3) statistical software. A correction factor (CF) was calculated for each equation to minimize the systematic bias during the back transformation of Ln values to biomass values (Sprugel 1983).

Selection, validation and comparisn of allometric model

The best-fit allometric model was selected based on lowest Akaike Information Criterion (AIC) and Residual Standard Error (RSE); and the highest Akaike Information Criterion Weight (AICw) and coefficient of determination (R^2) (Sileshi 2014; Mahmood et al. 2015, 2016b). But, models having RSE value greater than 0.30 may not be selected as best fit (Sileshi 2014). A variance influence factor (VIF) test was performed to check the multicollineary among the identical predictor variables of each model. Models having VIF > 5 indicate the existence of multicollineary among the identical independent variables (Sileshi 2014). The selected models of leaf, branch, bark and stem biomass were validated using sample trees of Data Set B in terms of model efficiency (ME). Modes having ME value less than zero cannot be recommended, while models with ME value close to 1 are considered to be "near-perfect" (Mayer and Butler 1993).

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

where Yp = Predicted biomass from model, Yo = Observed biomass in field measurement, and $\bar{Y}$ = Mean of the observed biomass.

Data Set B was used to compare the ME of the most frequently used pan-tropical biomass models of Brawn (1997) and Chave et al. (2005). Regression between Yp (in the X-axis) and Yo (in the Y-axis) was calculated for the best fit and compared pan-tropical models using the Data Set B (Table 8). Significance of slope (b = 1) and intercept (a = 1) were also tested according to Piñeiro et al. (2008). This analysis helped to understand graphically the over- or under-estimation of the predicted biomass using each model from 1:1 line (Sileshi 2014). Unless otherwise noted in the following text, the alpha level for all statistical analyses was 0.05.

Table 2 Frequently used biomass models

Model No.	Models	Sources
1	Ln (Biomass) = $a + b$ Ln (D)	Brown (1997)
2	Ln (Biomass) = $a + b$ Ln (D) + c Ln (H)	Nelson et al. (1999)
3	Ln (Biomass) = $a + b$ Ln (D) + c Ln (H) + d Ln (W)	Nelson et al. (1999) and Chave et al. (2005)
4	Ln (Biomass) = $a + b$ Ln (D) + c (Ln (D))^2 + d (Ln (D))^3 + e Ln (W)	Chave et al. (2005)
5	Ln (Biomass) = $a + b$ Ln (D^2*H*W)	Brown et al. (1989), Chave et al. (2005, 2014)
6	Ln (Biomass) = $a + b$ Ln (D) + c Ln (W)	Djomo et al. (2010)
7	Ln (Biomass) = $a + b$ Ln (D^2*H) + c Ln (W)	Djomo et al. (2010)
8	Ln (Biomass) = $a + b$ Ln (D^2*H)	Brown et al. (1989) and Djomo et al. (2010)

Results

Carbon in different components of samples tree species and wood density

Carbon concentration varied significantly by tree component as well as species. Among tree components, leaf contained lower concentration (43–48%) of carbon, while significantly higher concentration (48–49%) of carbon was recorded in stem (Table 3). Wood density values of the sampled tree species were found to vary significantly with species. Higher (822 kg m^{-3}) density was observed for *T. arjuna* followed by *T. bellirica* and lowest density (320 kg m^{-3}) was recorded for *A. malaccensis* (Table 1).

Allometric models for the smaller branches

The adjusted R^2 values of the allometric model for leaf, leaf containing smaller branches and woody parts of smaller branches varied by species. Lower values (0.2487 to 0.8608) of adjusted R^2 were observed for leaves, while higher values (0.7270 to 0.9767) were recorded for woody parts of smaller branches (Tables 4, 5, 6).

Allometric biomass models and their validiation

The ranges of DBH and H were 10.9 to 62 cm and 6 to 24 m, respectively. Model 6 (Ln(Leaf) = − 11.0054 + 1.2476*Ln(D) + 1.355*Ln(W)) was selected as the best allometric model for leaf with adjusted R^2 value of 0.3152. In case of branch, Model 4 (Ln (Branch) = − 31.244 + 29.4233*Ln (D) − 9.2811*(Ln (D))^2 + 1.0181*(Ln (D))^3 + 0.4927*Ln (W)) showed lowest AIC and RSE, and highest AICw, adjusted R^2, and variance influence factor (VIF) for multicollineary test than the reference value (5) compared to other tested models. While, Model 3 (Ln (Branch) = − 4.0022 + 2.0826*Ln (D) − 0.5103*Ln (H) + 0.4863*Ln (W)) with second lowest AIC (224.494)

Table 3 Carbon concentration in different parts of samples tree species

Scientific name	Carbon (%) in tree parts			
	Leaf	Branch	Bark	Stem
Albizia spp.	47.90 ± 0.55	47.71 ± 0.48	47.55 ± 0.96	48.92 ± 0.34
Aquilaria malaccensis	45.70 ± 0.87	47.31 ± 0.80	45.81 ± 0.69	48.75 ± 0.45
Artocarpus chaplasha	46.23 ± 1.23	44.08 ± 0.50	44.91 ± 0.84	47.30 ± 0.62
Dipterocarpus turbinatus	47.00 ± 0.56	47.67 ± 0.98	46.02 ± 1.06	48.62 ± 0.67
Eucalyptus camuldalensis	46.31 ± 0.73	47.20 ± 1.09	45.66 ± 1.23	49.88 ± 0.26
Hevea brasiliensis	46.64 ± 0.82	47.21 ± 0.54	48.88 ± 0.79	49.43 ± 0.49
Hopea odorata	46.91 ± 1.41	45.30 ± 0.37	45.77 ± 0.44	48.24 ± 0.67
Lagerstroemia speciosa	42.96 ± 0.85	46.00 ± 1.06	45.11 ± 0.38	49.21 ± 0.78
Senna siamea	47.93 ± 0.59	47.92 ± 0.89	46.88 ± 0.49	49.51 ± 0.22
Swietenia mahagoni	46.42 ± 0.48	45.53 ± 0.27	45.55 ± 0.91	49.10 ± 0.37
Syzygium grande	47.10 ± 0.67	47.06 ± 0.22	47.33 ± 0.88	48.98 ± 0.49
Tectona grandis	44.80 ± 0.77	45.86 ± 0.97	44.86 ± 0.67	49.24 ± 0.57
Terminalia arjuna	45.49 ± 0.83	44.75 ± 1.26	40.44 ± 0.58	48.84 ± 0.29
Terminalia bellirica	43.34 ± 1.08	43.39 ± 0.83	45.99 ± 0.61	49.54 ± 0.38

Table 4 Best fit allometric models for leaf biomass for the Hill zone of Bangladesh

Species	Allometric model	Adjusted R^2	RSE	AIC	CF
Albizia spp.	Ln (Leaf) = − 4.8263 + 2.2000*Ln (Base dia)	0.6630	0.4590	30.7924	1.1111
Aquilaria malaccensis	Ln (Leaf) = − 4.3355 + 1.8418*Ln (Base dia)	0.6588	0.4913	66.2753	1.1283
Artocarpus chaplasha	Ln (Leaf) = − 4.5919 + 2.1181*Ln (Base dia)	0.4355	0.5605	77.8736	1.1701
Dipterocarpus turbinatus	Ln (Leaf) = − 3.5536 + 1.6613*Ln (Base dia)	0.6995	0.3908	41.3420	1.0794
Eucalyptus camuldalensis	Ln (Leaf) = − 3.3784 + 1.6193*Ln (Base dia)	0.8608	0.2607	6.5590	1.0346
Hevea brasiliensis	Ln (Leaf) = − 3.1346 + 1.4186*Ln (Base dia)	0.4171	0.4487	55.8321	1.1059
Hopea odorata	Ln (Leaf) = − 5.7394 + 2.7592*Ln (Base dia)	0.6825	0.3468	10.2186	1.0620
Lagerstroemia speciosa	Ln (Leaf) = − 4.3903 + 1.0905*Ln (Base dia)	0.2487	0.6780	84.3070	1.2584
Senna siamea	Ln (Leaf) = − 2.7384 + 0.9915*Ln (Base dia)	0.3660	0.4037	16.0980	1.0849
Swietenia mahagoni	Ln (Leaf) = − 5.1682 + 2.1500*Ln (Base dia)	0.8564	0.3799	41.8351	1.0748
Syzygium grande	Ln (Leaf) = − 3.2408 + 1.8044*Ln (Base dia)	0.5003	0.5647	71.7442	1.1728
Tectona grandis	Ln (Leaf) = − 3.8044 + 1.6906*Ln (Base dia)	0.5649	0.4906	66.1453	1.1279
Terminalia arjuna	Ln (Leaf) = − 4.6348 + 1.7160*Ln (Base dia)	0.6665	0.4298	107.4087	1.0968

Table 5 Best fit allometric models for leaf containing smaller branches (LCB) for the Hill zone of Bangladesh

Species name	Allometric model	Adjusted R^2	RSE	AIC	CF
Albizia spp.	Ln (LCB) = − 5.0858 + 2.2000*Ln (Base dia)	0.6630	0.4590	30.7924	1.1111
Aquilaria malaccensis	Ln (LCB) = − 4.6118 + 1.8418*Ln (Base dia)	0.6588	0.4913	66.2753	1.1283
Artocarpus chaplasha	Ln (LCB) = − 5.4560 + 2.1181*Ln (Base dia)	0.4355	0.5605	77.8736	1.1701
Dipterocarpus turbinatus	Ln (LCB) = − 3.8259 + 1.6613*Ln (Base dia)	0.6995	0.3908	41.3420	1.0794
Eucalyptus camuldalensis	Ln (LCB) = − 3.7565 + 1.6193*Ln (Base dia)	0.8608	0.2607	6.5590	1.0346
Hevea brasiliensis	Ln (LCB) = − 3.3129 + 1.4186*Ln (Base dia)	0.4171	0.4487	55.8321	1.1059
Hopea odorata	Ln (LCB) = − 5.6311 + 2.7592*Ln (Base dia)	0.6825	0.3468	10.2186	1.0620
Lagerstroemia speciosa	Ln (LCB) = − 3.9839 + 1.0905*Ln (Base dia)	0.2487	0.6780	84.3070	1.2584
Senna siamea	Ln (LCB) = − 2.7718 + 0.9915*Ln (Base dia)	0.3660	0.4037	16.0980	1.0849
Swietenia mahagoni	Ln (LCB) = − 4.7818 + 2.1500*Ln (Base dia)	0.8564	0.3799	41.8351	1.0748
Syzygium grande	Ln (LCB) = − 3.9056 + 1.8044*Ln (Base dia)	0.5003	0.5647	71.7442	1.1728
Tectona grandis	Ln (LCB) = − 4.9475 + 1.6906*Ln (Base dia)	0.5649	0.4906	66.1453	1.1279
Terminalia arjuna	Ln (LCB) = − 4.7956 + 1.7160*Ln (Base dia)	0.6665	0.4298	107.4087	1.0968
Terminalia bellirica	Ln (LCB) = − 4.9524 + 1.9584*Ln (Base dia)	0.6621	0.5707	79.4639	1.1769

and RSE (0.5364), and second highest AICw (0.0544) and adjusted R^2 (0.6458) was selected as the best model. In case of bark, Model 3 (Ln (Bark) = − 13.8954 + 1.0877*Ln (D) + 1.5993*Ln (H) + 1.4478*Ln (W)) showed better selection criteria with lowest AIC (181.326) and RSE (0.4576), and highest adjusted R^2 (0.8043). However, RSE for these allometric models (leaf, branch and bark) exceeded the reference level (Table 7). In other ways, the best fit allometric models of stem without bark and TAGB were Model 3 (Ln (Stem) = − 10.7248 + 1.6094*Ln (D) + 1.323*Ln (H) + 1.1469*Ln (W)) and Model 5 (Ln (TAGB) = − 6.6937 + 0.809*Ln (D^2*H*W)), respectively, where DBH = Diameter at Breast Height in cm, H = Total Height in m, and W = Wood Density (kg m^{-3}) (Table 7). The allometric models for leaves, branch and bark showed very low model efficiency (0.436 − 0.643) compared to the best-fit allometric models of stem without bark (0.948) and TAGB (0.837) (Table 8).

TAGB model comparison

The pan-tropical biomass model of Brown (1997) and Chave et al. (2005) showed lowest model efficiency (0.667 to 0.697) compared to the best-fit TAGB model of this study (Table 8). Visualization of the observed and

Table 6 Best fit allometric models for woody part of smaller branches for the Hill zone of Bangladesh

Species name	Allometric model	Adjusted R^2	RSE	AIC	CF
Albizia spp.	Ln (Woody part) = − 2.6978 + 2.2300*Ln (Base dia)	0.7270	0.4013	25.1448	1.0838
Aquilaria malaccensis	Ln (Woody part) = − 4.4371 + 2.7251*Ln (Base dia)	0.8996	0.3390	33.6234	1.0591
Artocarpus chaplasha	Ln (Woody part) = − 3.9161 + 2.8530*Ln (Base dia)	0.8124	0.3225	29.2441	1.0534
Dipterocarpus turbinatus	Ln (Woody part) = − 2.9422 + 2.4435*Ln (Base dia)	0.9145	0.2694	12.3242	1.0370
Eucalyptus camuldalensis	Ln (Woody part) = − 3.1944 + 2.5920*Ln (Base dia)	0.9551	0.2259	1.4004	1.0258
Hevea brasiliensis	Ln (Woody part) = − 2.6717 + 2.3207*Ln (Base dia)	0.7818	0.3325	30.6521	1.0568
Hopea odorata	Ln (Woody part) = − 2.8822 + 2.2256*Ln (Base dia)	0.9211	0.1228	− 8.4698	1.0076
Lagerstroemia speciose	Ln (Woody part) = − 2.8503 + 2.2832*Ln (Base dia)	0.8707	0.3263	27.2671	1.0547
Senna siamea	Ln (Woody part) = − 2.3945 + 2.3390*Ln (Base dia)	0.9767	0.1202	− 12.9755	1.0073
Swietenia mahagoni	Ln (Woody part) = − 4.4535 + 3.1104*Ln (Base dia)	0.9664	0.2506	6.8934	1.0319
Syzygium grande	Ln (Woody part) = − 2.6282 + 2.3104*Ln (Base dia)	0.8482	0.3092	23.5734	1.0490
Tectona grandis	Ln (Woody part) = − 2.9229 + 2.2546*Ln (Base dia)	0.7781	0.4003	48.2573	1.0834
Terminalia arjuna	Ln (Woody part) = − 3.5494 + 2.6620*Ln (Base dia)	0.8889	0.3340	61.9939	1.0574
Terminalia bellirica	Ln (Woody part) = − 3.2717 + 2.4554*Ln (Base dia)	0.9146	0.3076	25.0585	1.0484

predicted biomass demonstrated deviation in biomass estimation from the line of significance of slope ($b = 1$) and intercept ($a = 1$), which indicated that compared pan-tropical biomass models of Brown (1997) and derived best-fit TAGB models underestimated TAGB, while model of Chave et al. (2005) overestimated TAGB (Fig. 2).

Discussion

This study showed differences in carbon concentration among the tree components and species. Similarly, Thomas et al. (2012) reported wide variation in carbon concentration (41.9–51.6%) in stem tissue of tropical tree species

Accuracy in biomass estimation is largely depends on appropriate selection of allometric models (Nam et al. 2016). Model selection involves careful investigation of model parameters as described by Sileshi (2014), Birigazzi et al. (2015) and Mahmood et al. (2016a). This study included tree species having wide range of wood density and the best model for all components of trees included DBH, H and W as predictor variables (Table 7).

Most of the multi-species biomass models include wood density along with DBH and H as predictor variables to account for species-specific variability (Nelson et al. 1999; Chave et al. 2005, 2014; Djomo et al. 2010). The fitted model of leaf, branch and bark of this study showed lower adjusted R^2 as 0.3152, 0.6458 and 0.8043, respectively, compared to the recommended value (0.85) by UNFCCC (2011), hence these models might be less statistically reliable for future use. RSE of these models were higher than the reference level (Sileshi 2014), which could result in unrealistic biomass estimation for leaf, branch and bark by using these derived models (Mugasha et al. 2016). Thus, we failed to identify any best-fit model for leaf, branch and bark. A pool of tree species with wide range of DBH (10.9 to 62 cm) and H (6 to 24 m) were used to derive the allometric models. Each tree species has inherent architecture that varies with stage of growth, morphological characteristics, adaptation ability, physiological characteristics and site quality (Tomlinson and Zimmermann 1978; White 1979; Hibbs 1981). Tree architecture influences the form and shape of crown and stem growth, which shows identical morphological differences among tree species. Tree crown is highly variable with species and stages of growth (sapling, pole and tree), which can directly affect the branching pattern as well as biomass of leaves and branches (Jack et al. 1982; Echereme et al. 2015; Mugasha et al. 2016). Finally, DBH, H and W as predictor variables may not able to address the variability among the tree crown biomass of the sampled species. In such case, inclusion of some more predictor variables like crown dimensions (crown length and crown diameter) may increase the efficiency of multi species biomass models for leaf and branch. The selected models for stem and TABG were linear and/or interactive (Model 3) and compound derivatives (Model 5), respectively, and both showed statistical credibility to be selected as best fit model (Sileshi 2014; Birigazzi et al. 2015)

Accurate estimation of biomass stock is needed, but some error is always associated with biomass estimation using allometric models. Our best fit TAGB models showed higher efficiency compared to the frequently used pan-tropical models of Brown (1997) and Chave et al.

Table 7 Allometric models of leaf, branch, stem, bark and total above-ground biomass (TAGB) for the Hill zone of Bangladesh

Model No.	a	b	c	d	e	Adjusted R^2	RSE	AIC	AICw	CF	VIF
Leaf biomass											
1	− 2.5678	1.3113				0.2265	0.9484	340.017	0.0005	1.5679	
2	− 2.7094	1.2281	0.1577			0.2209	0.9479	341.883	0.0002	1.573	b = 2.120, c = 2.120
3	− 10.9941	1.3028	− 0.1059	1.3685		0.3098	0.8885	327.952	0.1928	1.4938	b = 2.128, c = 2.173, c = 1.031
4	− 3.1924	− 5.2435	1.7388	− 0.1511	1.3651	0.3055	0.8875	329.687	0.0810	1.4976	b = 22,169, c = 91,365, d = 23,847, e = 1.009
5	− 6.5846	0.5341				0.278	0.9163	331.548	0.0319	1.5217	
6*	− 11.0054	1.2476	1.355			0.3152	0.8887	326.019	0.5067	1.4891	b = 1.006, c = 1.006
7	− 10.915	0.4726	1.3019			0.304	0.896	328.017	0.1866	1.4989	b = 1.011, c = 1.011
8	− 2.9085	0.5053				0.2231	0.9505	340.559	0.0004	1.5711	
Branch biomass											
1	− 1.296	1.8014				0.6225	0.558	231.231	0.0019	1.1684	
2	− 0.9276	2.0728	− 0.4823			0.6313	0.5493	229.002	0.0057	1.1642	b = 2.215, c = 2.037
3*	− 4.0022	2.0826	− 0.5103	0.4863		0.6458	0.5364	224.494	0.0544	1.1572	b = 2.216, c = 2.041, c = 1.007
4	− 31.244	29.4233	− 9.2811	1.0181	0.4927	0.6627	0.5215	218.828	0.9255	1.1492	b = 20,373, c = 85,252, d = 22,558, e = 1.007
5	− 5.4054	0.6433				0.5781	0.5898	246.349	0.0000	1.19	
6	− 4.2636	1.7957	0.4661			0.6355	0.5462	227.437	0.0125	1.1622	b = 1.000, c = 1.005
7	− 4.2408	0.6554	0.444			0.578	0.5877	247.368	0.0000	1.1901	b = 1.000, c = 1.005
8	− 1.4237	0.6584				0.5668	0.5977	249.928	0.0000	1.1955	
Bark biomass											
1	− 3.4563	2.0054				0.5853	0.6712	281.485	0.0000	1.2526	
2	− 4.7415	1.0585	1.6828			0.6898	0.5783	242.968	0.0000	1.1835	b = 2.215, c = 2.037
3*	− 13.8954	1.0877	1.5993	1.4478		0.8043	0.4576	181.326	0.9992	1.1122	b = 2.216, c = 2.041, c = 1.007
4	− 20.7583	8.0272	− 1.5001	0.1165	1.5037	0.7086	0.5562	236.392	0.0000	1.1715	b = 20,372, c = 85,252, d = 22,558, e = 1.007
5	− 10.0409	0.8449				0.7594	0.5112	207.401	0.0000	1.1396	
6	− 13.0764	1.9869	1.5111			0.7087	0.5604	234.416	0.0000	1.1714	b = 1.000, c = 1.005
7	− 13.7331	0.8063	1.4766			0.7809	0.486	195.653	0.0008	1.1263	b = 1.000, c = 1.005
8	− 4.3648	0.8163				0.6627	0.6053	253.385	0.0000	1.201	
Stem biomass											
1	− 2.4128	2.3679				0.7759	0.5067	205.039	0.0000	1.137	
2	− 3.4738	1.5862	1.3891			0.8438	0.4215	156.966	0.0000	1.0936	b = 2.215, c = 2.037
3*	− 10.7248	1.6094	1.323	1.1469		0.9121	0.3151	79.7847	0.9486	1.0517	b = 2.216, c = 2.041, c = 1.007
4	− 26.6939	16.8754	− 4.1473	0.3885	1.195	0.8521	0.407	151.457	0.0000	1.0884	b = 20,372, c = 85,252, d = 22,558, e = 1.007
5	− 9.3924	0.9467				0.9052	0.3295	88.0085	0.0155	1.0558	
6	− 10.0473	2.3532	1.1992			0.8498	0.4133	151.626	0.0000	1.0899	b = 1.000, c = 1.005
7	− 10.6451	0.9336	1.161			0.907	0.3251	86.3377	0.0358	1.0547	b = 1.000, c = 1.005

Table 7 continued

Model No.	a	b	c	d	e	Adjusted R^2	RSE	AIC	AICw	CF	VIF
8	− 3.2791	0.9414				0.8375	0.4315	161.347	0.0000	1.0976	
Total above-ground biomass											
1	− 0.9559	2.0926				0.8574	0.34	96.4705	0.0000	1.0595	
2	− 1.5154	1.6804	0.7325			0.8837	0.3059	69.7623	0.0000	1.0483	*b* = 2.237, *c* = 2.239
3	− 6.7869	1.6972	0.6845	0.8338		0.9347	0.2283	− 7.7995	0.1898	1.0268	*b* = 2.238, *c* = 2.244, *c* = 1.006
4	− 23.5157	18.08	− 4.9423	0.5029	0.8655	0.9126	0.2632	32.8711	0.0000	1.0361	*b* = 20,578, *c* = 84,708, *d* = 22,129, *e* = 1.005
5*	− 6.6937	0.809				0.9349	0.2298	− 10.0577	0.5870	1.0268	
6	− 6.4364	2.0821	0.8608			0.9114	0.267	32.766	0.0000	1.0366	*b* = 1.002, *c* = 1.004
7	− 6.8121	0.8078	0.8293			0.9344	0.2297	− 8.1243	0.2232	1.0269	*b* = 1.000, *c* = 1.004
8	− 1.5506	0.8134				0.8842	0.3064	68.1665	0.0000	1.048	

Model having (*) indicating best fit model

Table 8 Validation of selected models of this study and comparison with commonly used pan-tropical biomass models

Model no	Tree parts	Selected models	R^2	ME
6	Leaf	Ln (Leaf) = − 11.0054 + 1.2476*Ln (D) + 1.355*Ln (W)	0.3152	0.436
3	Branch	Ln (Branch) = − 4.0022 + 2.0826*Ln (D) − 0.5103*Ln (H) + 0.4863*Ln (W)	0.6458	0.543
3	Bark	Ln (Bark) = − 13.8954 + 1.0877*Ln (D) + 1.5993*Ln (H) + 1.4478*Ln (W)	0.8043	0.643
3	Stem	Ln (Stem) = − 10.7248 + 1.6094*Ln (D) + 1.323*Ln (H) + 1.1469*Ln (W)	0.9121	0.948
5	TAGB	Ln (TAGB) = − 6.6937 + 0.8090*Ln (D^2*H*W)	0.9349	0.837
1	Brown (1997) (Moist)	TAGB = exp(− 2.134 + 2.5430*Ln (D))		0.697
4	Chave et al. (2005)	TAGB = W*exp(− 1.499 + 2.148*Ln(D) + 0.207*(Ln (D))^2 − 0.0281*(Ln(D))^3)		0.667

(2005). Such comparison is essential to assess the uncertainty and suitability of the derived model and frequently used pan-tropical biomass models at local scale (Nam et al. 2016). Numerous studies have demonstrated that biomass estimation using pan-tropical models generated higher uncertainty than did locally developed models, for instance the biomass study of Kalimantan (Basuki et al. 2009), Sarawak (Kenzo et al. 2009), Columbia (Alvarez et al. 2012; Ngomanda et al. 2014), Indonesia (Manuri et al. 2014; Maulana et al. 2016), and Vietnam (Nam et al. 2016). However, the context provided by this study and the results presented herein demonstrate that our derived best-fit model will able to accurately estimate TAGB for the hill zone of Bangladesh.

Conclusions

Best fit biomas models for leaf, branch and bark were not identified due to unacceptably low model efficiency. Diameter at breast height, height and wood density as predictor variables might not be enough to address the variabliity of leaf and branch biomass for a pool of tree species having different crown architecture. The best fit total aboveground biomass model of this study showed higher model efficiency compared to some frequently used pan-tropical models. The results of this study demonstrate that the development of local models derived from an appropriate sample of representative species with appropriate predictor variables can greatly improve the estimation of total aboveground biomass. The best-fit models presented here can provide greater confidence when estimating biomass, carbon stock, and monitoring of forest

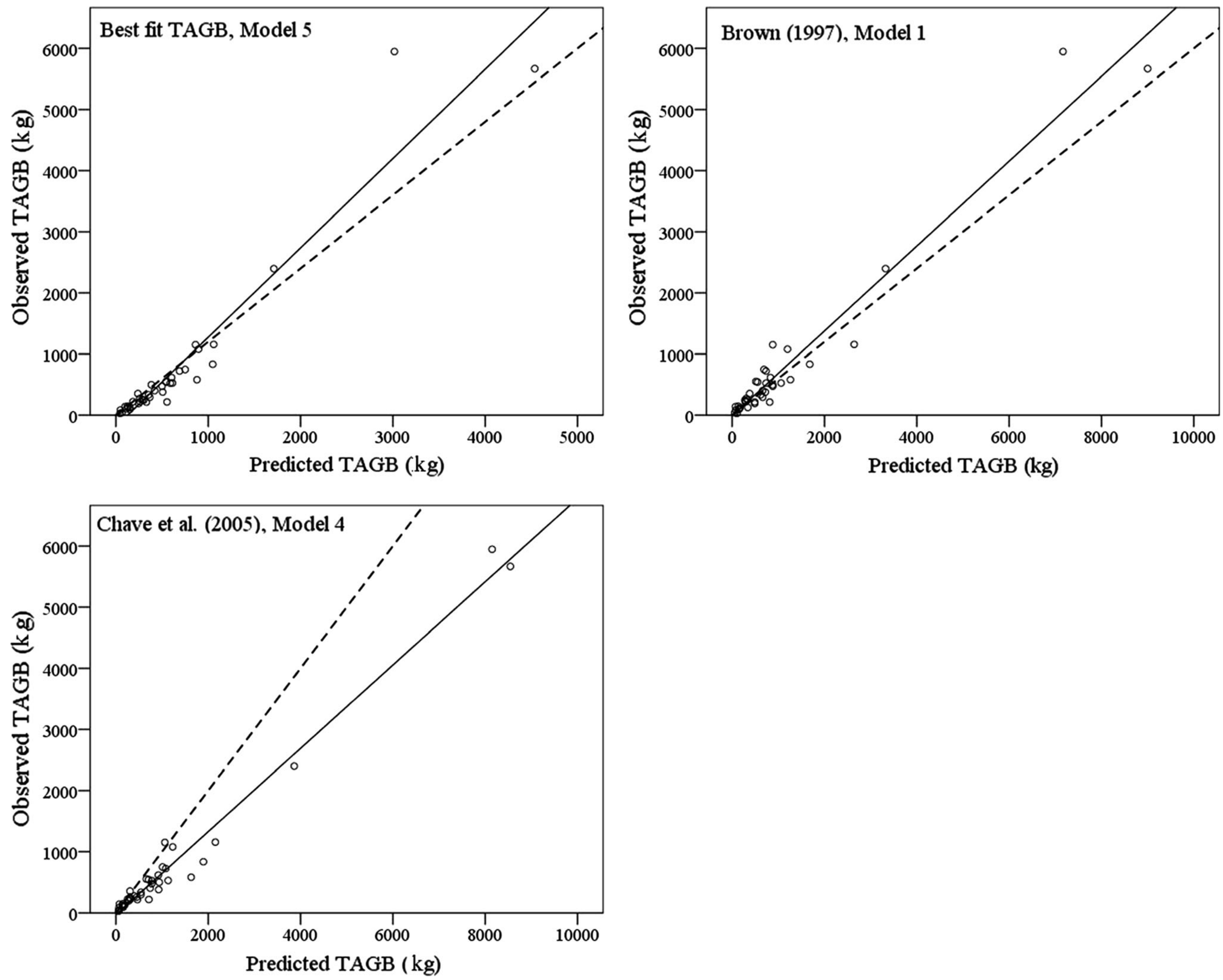

Fig. 2 Regression between observed and predicted values of frequently used pan-tropical biomass models of Brown (1997) and Chave et al. (2005). Solid line is the regression line and broken line is the significance of slope ($b = 1$) and intercept ($a = 1$)

productivity. This might help to guide new management initiatives for the Hill zone of Bangladesh.

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