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Simultaneous estimation of above- and below-ground biomass in tropical forests of Viet Nam

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ABSTRACT

For carbon accounting or for developing REDD+ (Reducing Emissions from Deforestation and forest Degradation) programs, allometric equations for estimating both above-ground biomass (AGB) and below-ground biomass (BGB) are useful. We developed systems of weighted nonlinear allometric equations to estimate total, above- and below-ground biomass for Dipterocarp forests (DF) and Evergreen broadleaf forests (EBLF) in the Central Highlands of Viet Nam, as well as for a dominant plant family (Dipterocarpaceae; Dip) in the DF. A total of 175 trees were destructively sampled for both AGB and BGB, with whole root extraction as the method of BGB sampling. Different equation forms for AGB and BGB incorporating diameter at breast height (D), tree height (H), wood density (WD) and crown area (CA) were evaluated. The best system of equations for the DF, Dipterocarpaceae in the DF, and EBLF was selected based on validation statistics of percent bias (PBias), mean absolute percentage error (MAPE), and root mean squared percent error (RMSPE). All three systems of equations developed in this study used $D^2 \times H \times WD$ as a predictor for AGB and a simpler BGB equation form with either $D^2 \times H$ or D as the sole predictor variable. The addition of WD or CA to BGB equation forms did not substantially improve validation statistics over simpler forms. These allometric equations should contribute to advancing our understanding of carbon distribution of trees in these tropical ecosystems.

1. Introduction

Tree roots are an important component in the world's terrestrial carbon budget, with up to half of the annually cycled carbon in forests contributed by roots systems (Vogt et al., 1996). However, due to the inherent increase in cost and time associated with below-ground woody biomass (BGB) measurements, most carbon-related research has focused on above-ground biomass (AGB). While relatively few studies have focused on developing equations for estimating BGB based on easy to measure tree variables, a need still exists for reliable BGB equations (Yuen et al., 2013; Ziegler et al., 2012). This is especially critical for tropical forests in Southeast Asia, as the majority of the few studies performed for tropical forest have focused on sites from South and Central America (Hertel et al., 2009).

The United Nations Framework Convention on Climate Change (UNFCCC) program for Reducing Emissions from Deforestation and forest Degradation (REDD+) works with developing countries to promote forest carbon conservation as a means of reducing greenhouse gas emissions. Viet Nam is one of the countries participating in the REDD+ program and is currently updating and producing allometric equations for the estimation of forest biomass and carbon.

Early biomass equations were single-entry equations relating total and component biomass to diameter at breast height (D) through a logarithmic relation. With the increase in demand of forest biomass estimates, considerable efforts have been made in estimating total and component biomass. Since Parresol (2001) introduced the use of seemingly unrelated regression (SUR) to simultaneously fit component and total biomass equations, it became a standard for developing biomass equations because it ensured the additivity among component and total biomass predictions. Additionally the use of SUR over ordinary least squares regression allowed for more efficient parameter estimation as error terms in different component models were correlated (Poudel and Temesgen, 2016b).

Since the publication of Parresol's paper, SUR has been used by many researchers in fitting biomass equations (e.g. Lambert et al., 2005; Brandeis et al., 2006; Navar, 2009; Ritchie et al., 2013; Zhao

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et al., 2015; Poudel and Temesgen, 2016a). Recently, Poudel and Temesgen (2016a, 2016b) used multinomial log-linear regression and Dirichlet regressions for a simultaneous prediction of proportion of biomass in different aboveground components. The predicted proportions were then applied to the predicted total aboveground biomass obtained from a simple log-log model. Zhao et al. (2016) used this approach to predict proportions of biomass in different aboveground components of loblolly pine trees simultaneously. However, the literature on fitting simultaneous equations for above- and below-ground biomass is scarce.

If AGB and BGB are treated as components of a tree's total biomass (TB; kg), SUR can be used to simultaneously fit system of allometric equations in order to estimate TB. Common methods for estimating AGB and BGB include the use of log-linear models (Basuki et al., 2009; Brown, 1997; Chave et al., 2005; IPCC, 2003), and power model (Chave et al., 2014; Kenzo et al., 2009a, 2009b) with or without weighting. However reparametrizing non-linear power models can result in models trivially equivalent to log-linear models (Picard et al., 2015). Predictor variables used in the estimation of tree biomass include D (cm), total tree height (H; m), wood density (WD; g/cm^3), or some combination thereof such as $D^2 \times H$ (D^2H; m^3) or $D^2 \times H \times WD$ (D^2HW; kg), which serve as approximations for volume and AGB, respectively (Picard et al., 2015). Recently, it has also been shown that incorporating a measurement of crown diameter (m) can improve the accuracy of biomass estimates (Huy et al., 2016a; Dietz and Kuyah, 2011; Henry et al., 2010).

Additional difficulty exists in modelling tree biomass for tropical forests due to their complex nature in both structure and diversity of species. Therefore, researchers have commonly focused on developing pan-tropical or generic multi-species models (e.g. Basuki et al., 2009; Brown, 1997; Chave et al., 2005, 2014; IPCC, 2003). While valuable information can be provided by generic models, results can be biased if they are applied to a particular forest type under, or not, represented in that model's development data (Chave et al., 2014). Thus, considering differences in forest type when developing models is beneficial for more accurate tree biomass estimation (Temesgen et al., 2015).

This study contributes to that larger body of work by estimating total tree biomass (TB), as the sum of above- and below-ground biomass components, for tropical forests of Viet Nam. The primary goals of this study are to: (i) develop reliable and accurate models for the estimation of TB, AGB, and BGB in two forest types of Viet Nam; (ii) examine if family-specific equations for a dominant plant family (Dipterocarpaceae) provide more accurate estimations of biomass than broad forest type specific equations; and (iii) assess the predictive abilities of simultaneous fitting strategy for estimating AGB and BGB.

2. Materials and methods

2.1. Study sites

This study was carried out in the Central Highlands eco-region of Viet Nam (Fig. 1); one of eight such zones that partition the country and consider environmental variability with respect to soil, climate, and elevation (Phuong and Linh, 2011; Sola et al., 2014). The Central Highlands has the highest cover of tropical forests of all eco-regions in Viet Nam. We focused on the main tropical forest types of this region: the dipterocarp forest (DF) and the evergreen broadleaf forest (EBLF). The EBLF study sites were located in the provinces of Gia Lai, Dak Lak, and Dak Nong, while the DF sites were located in Dak Lak province (Fig. 1).

Both forest types are structurally complex with mixed-species composition. The primary plant family in the DF is Dipterocarpaceae and dominant genera of that family include *Dipterocarpus* and *Shorea*. Elevation for the DF sites ranged from 197 to 417 m. Mean annual precipitation and temperature for DF are 1600 mm and 25.5 °C, respectively. Stand density of live trees ⩾5 cm D for DF ranged between 256 and 1292 trees per hectare (TPH) and basal area ranged between 3.3 m^2/ha and 23.0 m^2/ha. Unlike the DF, the EBLF is not dominated by any particular plant family, although members of the Fagaceae, Myrtaceae, and Lauraceae plant families are common. The TPH for EBLF was between 370 and 3330 while basal area ranged between 8.1 m^2/ha and 49.0 m^2/ha. Elevation for the EBLF sites ranged from 403 to 1068 m. Mean annual precipitation ranged from 2100 to 2500 mm with mean annual temperatures from 22.2 to 25.0 °C. The dry season lasts for 3 months in both forest types.

2.2. Data collection

A total of 27 plots were installed in EBLF (14 plots; 20 × 100 m) and DF (13 plots; 50 × 50 m) of the Central Highlands. Within a plot, species and D was recorded for all live trees ⩾5 cm D. In each plot, a sample of trees were selected for AGB measurements, and a sub-sample of those trees were additionally selected for BGB measurements. Sample tree selection for biomass focused on the main species present on the plot with the number of trees sampled determined by the ratio of trees in each 10 cm diameter class. Fig. 2 shows representatives of structure of D and BA distributions in both forest types. A sample tree's selection for additional sampling of BGB was determined similarly to the selection of AGB trees but at a lower selection rate due to cost. The BGB tree selection rate for DF sites was 60–65% of trees sampled for AGB. The selection rate was lower for EBLF sites (30–35%) as this forest type had higher average tree density than DF sites. In this study, we only used sample trees that were destructively sampled both ABG and BGB. This resulted in a total of 175 sample trees, representing 48 species, 40 genera, and 28 families (Table 1).

For sample trees used in this study, an additional measurement of crown diameter (m) was recorded before felling and was obtained as the average of two cardinal direction (North-South and East-West) measurements. H was measured after sample trees were felled. For large trees, the stems were cut to a maximum weight of 200 kg to obtain total above-ground fresh weight. Whole sample tree root systems were excavated for each tree and coarse root measurements were obtained. Use of industry vehicles was necessary for some large trees to uproot the entire root system. Smaller roots were then excavated by hand. In this study the term coarse root refers to roots that were able to be excavated by hand, there was no attempt in this study to collect fine root data and no diameter break was set to differentiate between coarse and fine root, as has been done in other studies.

The fresh-weight of tree components (leaves, branches, stem with bark, and coarse roots) were also recorded in the field. To determine the fresh-to-dry mass ratio of each component, samples were sealed and taken to the laboratory. For each tree, roots were classified based on the sample tree's D into 3 sizes categories (large, medium, and small), and approximately 300 g was sampled from each of these three categories. Tree stem samples of wood (500 g), bark (300 g), and wood disks (for calculating WD) were taken at five replications along a tree's stem. For each tree, three branch samples (500 g per sample) were taken; the first sample from the largest branch, the second from a medium sized branch, and lastly a sample from the smallest branch. Two foliage samples (300 g per sample) of new and old leaves were taken for each tree.

In the lab, fresh volume of wood samples was obtained using the water displacement method. All samples were then chipped into small pieces and dried at 105 °C until a constant weight was

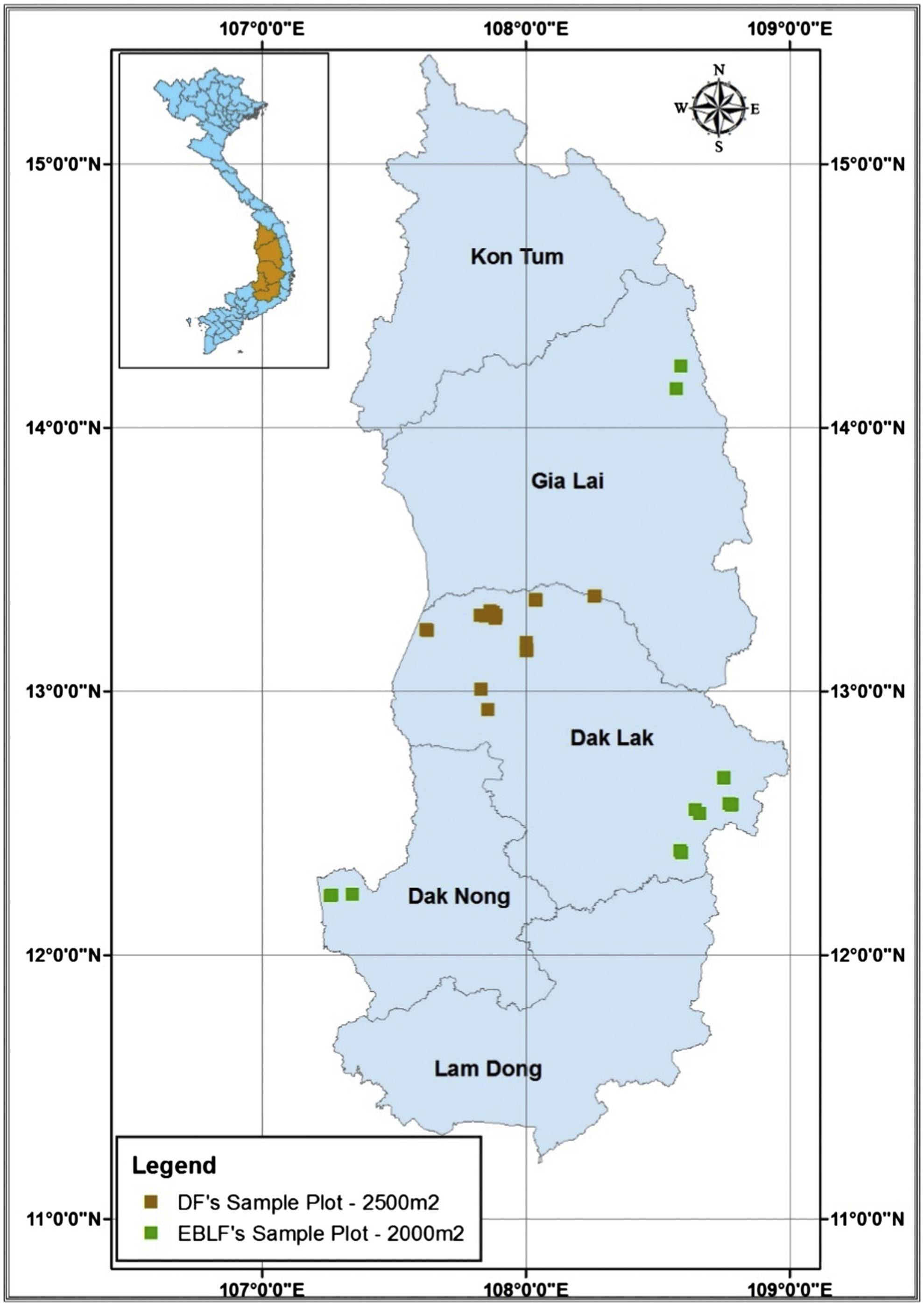

Fig. 1. Location of sample plots in study sites for the Dipterocarp Forest (DF) and Evergreen Broadleaf Forest (EBLF) types in the Central Highlands of Viet Nam.

achieved. Total above- and below-ground dry weights of a tree (AGB and BGB, respectively; kg) were calculated by multiplying the fresh weight of components by their respective fresh-to-dry ratios and summing across the appropriate components. WD of a sample was calculated as the ratio of dry weight to fresh volume of each sample, and WD of a sample tree was calculated as the arithmetic average WD of all that tree's samples. Crown area (CA; m^2) was calculated based on crown diameter ($CA = \pi/4 * (crowndia\, meter)^2$). Summary data on trees destructively sampled for both AGB and BGB in the DF, Dipterocarpaceae in the DF, and EBLF is shown in Table 2.

2.3. Model development

Separate equations were fit for the DF and EBLF forest types. Several nonlinear models were examined for the AGB and BGB components. Parameters of the component and TB models were estimated by simultaneously fitting a system of equations with the SUR. This approach constrained the component and TB models so that the sum of the predicted biomass by component models equalled the biomass predicted from the TB model.

Models tested in this study were of the following general form:

$$AGB_i = \alpha_1 * X_{1i}^{\beta_1} + \varepsilon_{1i} \quad (1)$$

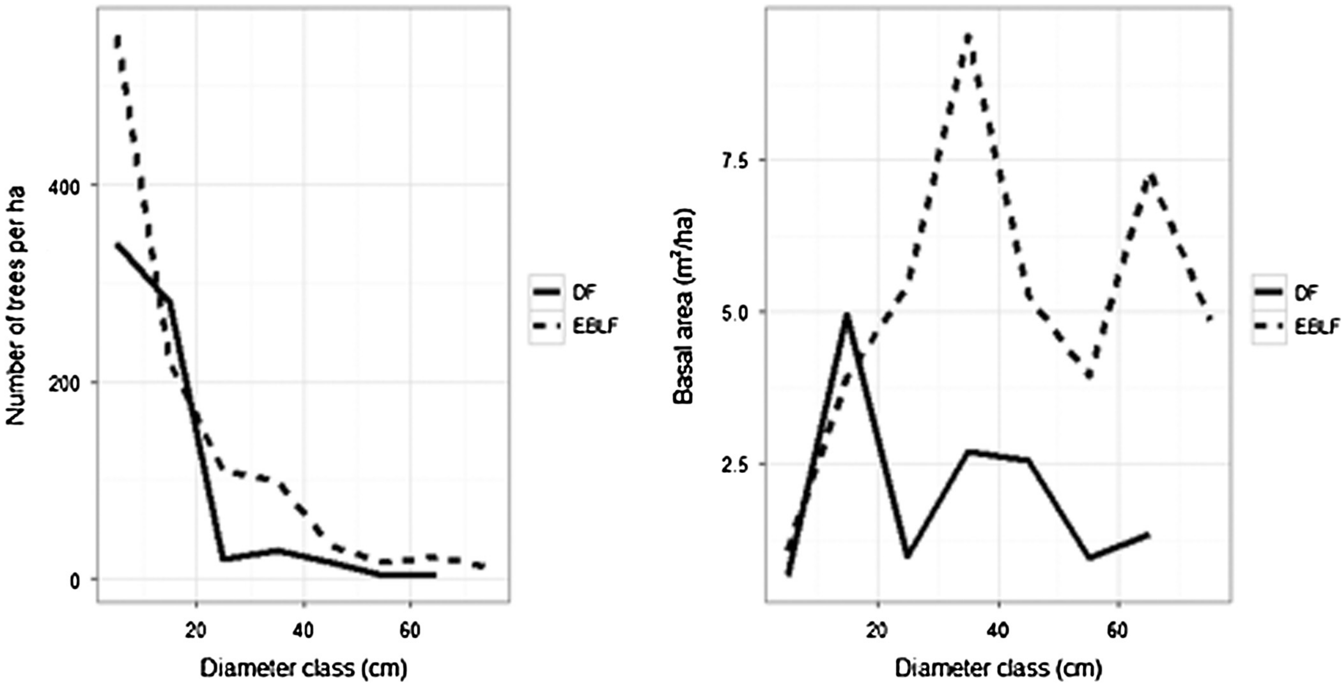

Fig. 2. Structure of both the Dipterocarp Forest (DF) and Evergreen Broadleaf Forest (EBLF) types in the Central Highlands of Viet Nam.

Table 1
Number of destructively sampled trees (N) for both AGB (kg) and BGB (kg) by family, genus, and species.

Dipterocarp Forest			Evergreen Broadleaf Forest		
Family	Genus species	N	Family	Genus species	N
Chrysobalanaceae	*Parinari anamensis* Hance	3	Anacardiaceae	*Semecarpus sp.*	1
Combretaceae	*Terminalia alata*	5	Annonaceae	*Alphonsea sp.*	1
	T. corticosa	5	Apocynaceae	*Alstonia scholaris*	1
Dilleniaceae	*Dillenia sp*	1	Araliaceae	*Trevesia palmata*	2
Dipterocarpaceae	*Dipterocarpus obtusifolius*	7	Burseraceae	*Canarium album*	1
	D. tuberculatus	42	Cannabaceae	*Trema orientalis*	1
	Shorea obtusa	10	Clusiaceae	*Garcinia oblongifolia*	4
	S. siamensis Miq.	6		*G. sp.*	1
Euphorbiaceae	*Aporosa sp*	6	Ebenaceae	*Diospyros ehretioides*	1
Lecythidaceae	*Careya arborea* Roxb.	2	Euphorbiaceae	*Aporosa microcalyx*	1
Leguminosae	*Dalbergia nigrescens*	1	Fagaceae	*Castanopsis sp.*	6
	Sindora siamensis	1		*Lithocarpus annamensis*	2
	Xylia xylocarpa	7	Lauraceae	*Cinnamomum iners*	2
Loganiaceae	*Strychnos nux-blanda*	1		*C. parthenoxylon*	1
Myrtaceae	*Syzygium cumini*	2		*Litsea glutinosa*	4
Rubiaceae	*Haldina cordifolia* (Roxb.) Ridsdale	1		*Phoebe lanceolata*	1
	Nauclea orientalis	5	Lecythidaceae	*Careya sphaerica*	1
			Leguminosae	*Dialium cochinchinense*	1
			Malvaceae	*Pterospermum heterophyllum*	1
			Meliaceae	*Aglaia annamensis*	1
				Chukrasia tabularis A. Juss	1
				Dysoxylum binectariferum	1
				Sandoricum sp.	3
				Walsura pinnata Hassk.	1
			Moraceae	*Streblus ilicifolius*	1
			Myrtaceae	*Syzygium sp.*	6
				S. zeylanicum	1
			Rosaceae	*Prunus arborea*	1
			Sapotaceae	*Donella sp.*	1
			Styracaceae	*Styrax annamensis*	1
			Symplocaceae	*Symplocos sp.*	2
			Ulmaceae	*Gironniera nervosa*	1
				G. subaequalis	1
			Other - Unidentified		15
Total number of sample trees used in this study		105			70

Table 2
Summary statistics for sample trees including D (cm), H (m), WD (g/cm^3), CA (m^2), AGB (kg), BGB (kg), and TB (kg) by forest type grouping.

Forest type	Summary	D	H	WD	CA	AGB	BGB	TB
DF (105)	mean	11.66	8.13	0.64	7.33	63.51	13.40	76.91
	min	3.40	2.80	0.38	0.38	1.53	0.51	2.60
	max	40.50	19.00	0.91	54.11	993.46	172.56	1166.02
	sd	6.77	3.55	0.10	8.98	135.67	22.93	157.45
Dipterocarpaceae in the DF (65)	mean	12.53	8.68	0.63	7.72	78.74	15.44	94.18
	min	4.90	3.80	0.38	0.38	1.53	0.51	2.60
	max	40.50	19.00	0.91	54.11	993.46	172.56	1166.02
	sd	7.23	3.62	0.10	9.71	164.30	27.35	190.29
EBLF (70)	mean	9.85	9.55	0.57	9.32	41.57	7.93	49.50
	min	4.70	4.30	0.35	1.13	2.93	0.49	3.49
	max	26.80	16.50	0.88	35.26	501.43	61.34	549.98
	sd	4.00	2.82	0.11	6.40	67.33	11.65	76.93

$$BGB_i = \alpha_2 * X_{2i}^{\beta_2} + \varepsilon_{2i} \tag{2}$$

$$TB_i = \alpha_1 * X_{1i}^{\beta_1} + \varepsilon_{1i} + \alpha_2 * X_{2i}^{\beta_2} + \varepsilon_{2i} \tag{3}$$

where AGB_i, BGB_i, and TB_i are the AGB, BGB, and TB respectively, for the i^{th} sample tree; α_z and β_z are parameters of the z^{th} model; X_{zi} is the predictor variable or combination of predictor variables associated with the i^{th} tree for the z^{th} model; and ε_{zi} is the random error term associated with the i^{th} tree for the z^{th} model and is assumed to be normally distributed with mean zero and constant variance.

Models were fit initially with D as the only predictor variable and then H, WD, combination variables, and CA were subsequently added as additional predictor variables. Preliminary analysis showed heterogeneous variance in the residuals when a non-linear model is fit. Therefore, residuals were weighted for the AGB and BGB non-linear model forms by either D or D^2 depending on the form of the diameter variable used in the model. If weighting was required for TB and the form of the weight differed between the AGB and BGB models, then both weight forms were examined as possible weights for TB.

As generic multi-species models may fail to take advantage of additional information related to structural differences between tree species, the feasibility of developing family specific models was investigated. In our study only the Dipterocarpaceae family had a large enough sample size (n = 65) to enable both model fitting and validation by family. Thus additional models were fit for the Dipterocarpaceae family in the DF forest type.

2.4. Model selection and validation

Based on the six available model input variables used in this study (D, H, WD, CA, D^{2}H, and D^{2}HW), a total of fourteen different model forms for AGB or BGB were possible. Investigating all possible combinations of model forms in a system of equations would result in examining 196 (14^2) different system of equations for each forest type. Therefore, to simplify the modelling process, the best model form for AGB was first determined outside of a system of equations. Then 14 systems of equations based on the selected AGB model form and varying BGB model forms were subsequently fit and compared.

To compare models, separate data sets were created for the DF, Dipterocarpaceae in the DF, and EBLF, consisting of trees destructively sampled for both AGB and BGB. Each of these three data sets was then was randomly split 200 times into model development (80%) and validation (20%) data sets. Validation statistics of percent bias (PBias), mean absolute percent error (MAPE), and root mean square percentage error (RMSPE) for each model were calculated as follows:

$$\text{PBias} = \frac{100}{R}\sum_{r=1}^{R}\sum_{i=1}^{n_r}\left[\frac{y_{ri}-\hat{y}_{ri}}{y_{ri}}\right]/n_r \tag{4}$$

$$\text{RMSPE} = \frac{100}{R}\sum_{r=1}^{R}\sqrt{\sum_{i=1}^{n_r}\left(\frac{y_{ri}-\hat{y}_{ri}}{y_{ri}}\right)^2/n_r} \tag{5}$$

$$\text{MAPE} = \frac{100}{R}\sum_{r=1}^{R}\sum_{i=1}^{n_r}\left[\frac{|y_{ri}-\widehat{y_{ri}}|}{y_{ri}}\right]/n_r \tag{6}$$

where R is the number of realizations (200); n_r is the number of trees per realization r; and y_{ri} and $\hat{y}_{ri}$ are the observed and predicted AGB, BGB, or TB for the i^{th} tree in realization r, respectively. Models that produced smaller values of validation statistics were preferred and simpler models were preferred when multiple models had comparable validation statistics. Initial starting values for the system of equations were based off of parameter estimates from refitting the selected AGB model form with the entire data set (model development and validation data). Final selected system of equation model forms were fit with the entire data set to derive parameter estimates, examine diagnostic plots, and determine significance of coefficients. Statistical analyses were performed using R statistical software (R Core Team, 2015) and SAS statistical software (SAS Institute Inc., 2013). SAS was used for fitting the weighted non-linear systems of equations using SUR. R was used for fitting preliminary AGB model forms and the calculation of summary statistics based on SAS results.

2.5. Evaluating need for a Dipterocarpaceae-specific model

The need for separate family-specific Dipterocarpaceae equations was assessed by directly modelling TB for the DF and including a Dipterocarpaceae indicator variable. Model forms examined included all of the fourteen model forms considered in this study for AGB and BGB estimation. After fitting models, the significance of the parameter associated with the Dipterocarpaceae indicator variable was examined to assess if separate model forms for the DF and the Dipterocarpaceae in the DF were required.

3. Results

3.1. Dipterocarp forest

Fourteen allometric models for AGB were fit outside of a system of equations with the model development data set for the DF forest type (Table 3). Only the *AGB = f(D^{2}H, WD, CA)* model form did not converge at all for any of the 200 simulations. Apart from this model form, all other forms that include variations of D, WD, and CA resulted in superior validation statistics, with substantial decreases in PBias and decreased in RMSPE. The best PBias and RMSPE statistics were observed when AGB was modelled as a function of D^{2}HW and CA. Therefore *AGB = f(D^{2}HW, CA)* was selected as the best overall AGB model form outside of a system of equations.

Table 3
Validation statistics including PBias, MAPE, and RMSPE for different model forms for estimating ABG by forest type grouping, as well as the number of time models converged in the 200 simulations (C).

AGB Model Form	Weight	DF				Dipterocarpaceae in the DF				EBLF			
		Pbias	MAPE	RMSPE	C	Pbias	MAPE	RMSPE	C	Pbias	MAPE	RMSPE	C
f(D)	*D*	−9.66	30.78	50.68	200	−8.11	26.34	38.16	200	1.11	30.7	41.19	200
f(D, H)	*D*	−4.54	31.11	45.77	200	−9.7	27.25	39.73	199	6.77	30.31	39.69	199
$f(D^2H)$	D^2	−4.24	33.26	43.65	200	−4.89	33.58	42.26	200	−4.62	28.34	40.96	42
f(D, WD)	*D*	5.67	25.77	36.75	200	−3.39	23.07	31.7	200	4.07	23.18	32.25	200
f(D, CA)	*D*	−9.99	28.42	40.2	179	−10.73	25.6	35.63	200	−5.3	32.13	44.48	96
f(D, H, WD)	*D*	5.21	26.25	36.96	200	−4.67	23.76	32.79	199	4.58	20.76	29.47	200
$f(D^2H, WD)$	D^2	3.26	27.58	34.66	141	1.06	26.08	31.54	122	2.19	21.68	30.8	200
$\boldsymbol{f(D^2HW)}$	$\boldsymbol{D^2}$	3.05	26.87	33.67	200	**1.78**	**25.75**	**30.88**	**200**	**2.19**	**21.15**	**30.29**	**200**
f(D, H, CA)	*D*	−8.56	27.26	37.66	200	−11.55	26.48	36.82	200	6	29.91	40.13	192
$f(D^2H, CA)$	D^2	−6.27	27.38	34.35	200	−7.84	29.22	35.65	200	1.22	28.42	39.56	200
f(D, WD, CA)	*D*	−0.3	21.55	31.36	200	−3.75	20.38	25.96	200	2.86	21.43	30.89	200
f(D, H, WD, CA)	*D*	−0.85	21.76	31.23	199	−4.42	21.02	26.83	196	4.53	20.41	29.42	199
$f(D^2H, WD, CA)$	D^2	–	–	–	0	–	–	–	0	–	–	–	0
$\boldsymbol{f(D^2HW, CA)}$	$\boldsymbol{D^2}$	**0.05**	**22.05**	**27.77**	**200**	−1.41	22.69	27.79	200	2.63	20.81	30.58	200

Selected best models are given in bold.

System of equations based on the selected AGB model form were then fit with the same 200 simulations of model development data (Table 4). The majority of models underestimated TB, with the exception of systems with BGB model forms *g(D, H, CA)* and *g(D, H, WD, CA)*, which resulted in a negative bias and the most extreme validation statistics for BGB and TB. The BGB model form *g(D, WD, CA)* resulted in lowest RMSPE and MAPE for TB and $g(D^2H)$ resulted in the lowest PBias for TB and similarly low RMSPE and MAPE. Since the system of equations with $BGB = g(D^2H)$ had superior validation statistics for TB, as well as few parameters to estimate, it was selected as the best preforming model.

While this system also resulted in good validation statistics for AGB including the best PBias, it had relatively high PBias and RMSPE for BGB. All parameter estimates for the selected system of equations were statistically significant at 95% level of significance (Table 5) and the TB component had an Adjusted R^2 (Adj. R^2) of 0.9766. Despite the suboptimal validation statistics for the BGB component, the BGB model still had an Adj. R^2 of 0.8863.

3.2. Dipterocarpaceae in the Dipterocarp forest

For the Dipterocarpaceae family in the DF, the model form $AGB = f(D^2H, WD, CA)$ was again the only model that failed to converge for any of the 200 simulations (Table 3). The majority of models resulted in negative PBias, with the exception of $f(D^2H, WD)$ and $f(D^2HW)$ which tended to under estimate AGB. These two forms resulted in low PBias and RMSPE. Adding CA as a covariate to $f(D^2HW)$ decreased RMSPE and MAPE, but resulted in a negative PBias. As the intended use of these models is to contribute to Viet Nam's UN-REDD program related efforts of accounting for forest carbon as a means of reducing greenhouse gas emissions, lower than actual carbon estimates were deemed preferable to overestimates for carbon accounting. Therefore the similar yet positive PBias of $f(D^2H, WD)$ and $f(D^2HW)$ was superior given the objectives of this modelling exercise. Therefore, the model form $AGB = f(D^2HW)$ was selected as it had similar validation statistics yet less parameters to estimate than $f(D^2H, WD)$.

Validation statistics for the system of equations fit based off of the selected AGB model form are shown in Table 6. The BGB model form *g(D, H, WD, CA)* again resulted in the most extreme validation statistics for BGB and TB. The majority of BGB model forms resulted in negative PBias for BGB and TB. Multiple model forms resulted in a RMSPE greater than 100 for BGB.

For TB validation statistics, the BGB model form *g(D)* resulted in the lowest RMSPE and second lowest MAPE. Adding H to this model resulted in the best PBias for TB, but substantially increased MAPE and RMSPE. Therefore, the system of equations with $BGB = g(D)$ was selected as the best preforming model for the Diptero-

Table 4
Validation statistics for different system of equations involving an AGB model form of $AGB = f(D^2HW, CA)$ and different model forms for BGB in the DF of Viet Nam. Validation statistics for AGB, BGB, and TB include PBias, MAPE, and RMSPE, as well as the number of time models converged in the 200 simulations (C).

BGB model form	Weight		AGB			BGB			TB			C
	BGB	TB	PBias	MAPE	RMSPE	PBias	MAPE	RMSPE	PBias	MAPE	RMSPE	
g(D)	*D*	*D*	−1.38	28.28	34.62	7.98	68.02	81.45	3.58	24.19	29.64	200
g(D, H)	*D*	D^2	10.29	28.24	33.55	−16.21	44.05	61.8	7.55	22.6	27.28	200
$\boldsymbol{g(D^2H)}$	$\boldsymbol{D^2}$	–	**−0.38**	**28.92**	**35.21**	**−15.24**	**49.94**	**69.81**	**0.15**	**22.54**	**27.49**	**200**
g(D, WD)	*D*	D^2	8.51	29.23	34.72	4.8	38.74	50.86	11.48	24.19	28.93	200
g(D, CA)	*D*	D^2	10.61	28.79	34.1	−6.63	44.06	60.42	9.91	23.04	27.38	198
g(D, H, WD)	*D*	D^2	8.56	28.42	33.89	6.48	42.99	57.78	11.88	24.12	28.97	200
$g(D^2H, WD)$	D^2	D^2	7.59	31.35	37.26	15.73	46.11	57.33	13.13	26.1	31.07	188
$g(D^2HW)$	D^2	D^2	8.64	31.35	37.09	8.85	40.42	53.05	12.4	26.19	31.17	200
g(D, H, CA)	*D*	*D*	−1.18	27.83	34.18	**	*	*	**	*	*	180
$g(D^2H, CA)$	D^2	D^2	7.34	31.46	37.27	5.79	50.74	64.92	10.35	24.49	29.32	190
g(D, WD, CA)	*D*	*D*	−2.69	29.17	35.78	−2.09	44.01	57.43	1.69	21.44	26.5	200
g(D, H, WD, CA)	*D*	D^2	5.63	30.8	36.76	**	*	*	**	*	*	154
$g(D^2H, WD, CA)$	D^2	D^2	7.38	30.52	36.27	2.42	42.85	55.25	10.23	24.93	30.1	200
$g(D^2HW, CA)$	D^2	D^2	7.99	30.88	36.61	5.24	42.16	55.14	11.14	25.08	30.08	200

Selected best models are given in bold.
* Value of $x > 10^5$.
** Value of $x < -10^5$.

Table 5
Number of trees (N), parameter estimates and approximate standard errors, root mean square error (RMSE), and Adj. R^2 for modelling TB as a system of equations with AGB and BGB components by forest type grouping.

Forest type (N)	Model form	Weight	Parameter	Estimate ± Approx. SE	RMSE	Adj. R^2
DF (105)	$AGB = f(D^2 HW, CA)$	D^2	a_1	0.79787 ± 0.0619	21.5046	0.9749
			b_1	0.667652 ± 0.0180		
			c_1	0.510242 ± 0.0269		
	$BGB = g(D^2 H)$	D^2	a_2	56.47582 ± 1.8289	7.7297	0.8863
			b_2	0.913188 ± 0.0343		
	$TB = f(\cdot) + g(\cdot)$	...	...	...	24.0601	0.9766
Dipterocarpaceae in the DF (65)	$AGB = f(D^2 HW)$	D^2	a_1	0.422367 ± 0.0599	34.1093	0.9569
			b_1	1.013458 ± 0.0191		
	$BGB = g(D)$	D	a_2	0.026438 ± 0.0116	8.5967	0.9012
			b_2	2.35221 ± 0.1238		
	$TB = f(\cdot) + g(\cdot)$	D	...	...	33.2432	0.9695
EBLF (70)	$AGB = f(D^2 HW)$	D^2	a_1	0.148215 ± 0.0270	14.5944	0.9530
			b_1	1.23945 ± 0.0286		
	$BGB = g(D)$	D	a_2	0.168916 ± 0.0651	6.1442	0.7219
			b_2	1.765361 ± 0.1231		
	$TB = f(\cdot) + g(\cdot)$	D^2	...	...	11.7650	0.9766

Note: All parameters significant at p-value < 0.0001.

Table 6
Validation statistics for different system of equations involving an AGB model form of $AGB = f(D^2HW)$ and different model forms for BGB for the Dipterocarpaceae in the DF of Viet Nam. Validation statistics for AGB, BGB, and TB include PBias, MAPE, and RMSPE, as well as the number of time models converged in the 200 simulations (C).

BGB model form	Weight		AGB			BGB			TB			C
	BGB	TB	PBias	MAPE	RMSPE	PBias	MAPE	RMSPE	PBias	MAPE	RMSPE	
g(D)	***D***	***D***	**0.9**	**31.09**	**37.77**	**−29.09**	**66.85**	**86.37**	**−2.63**	**24.29**	**30.89**	**200**
g(D, H)	D	D	−0.77	30.62	37.64	−33.95	81.36	124.56	−3.75	23.07	30.06	191
$g(D^2H)$	D^2	–	2.97	31.23	37.46	−46.34	62.32	87.26	−3.86	27	34.35	200
g(D, WD)	D	D^2	1.82	35.6	42.68	−16.53	59.47	85.38	0.13	29.99	37.51	145
g(D, CA)	D	D^2	−2.92	34.9	42.73	−13.72	57.74	76.37	−2.26	25.94	31.44	189
g(D, H, WD)	D	D^2	14.38	34.26	39.04	−35.68	95.27	161.19	8.99	26.98	32.4	130
$g(D^2H, WD)$	D2	D^2	−9.84	41.72	51.89	19.28	53.92	64.94	−1.15	31.97	39.52	161
$g(D^2HW)$	D2	D^2	−6.76	36.96	46.08	−2.74	42.96	56.22	−2.53	29.99	37.16	200
g(D, H, CA)	D	D^2	3.25	34.38	40.93	−40.62	125.54	226.16	0.67	24.31	32.6	195
$g(D^2H, CA)$	D2	D^2	−2.04	34.56	42.2	−30.13	63.7	83.92	−4.7	26.14	31.58	200
g(D, WD, CA)	D	D	−3.69	31.94	39.83	−28.32	76.61	106.53	−6.11	26.91	35.74	190
g(D, H, WD, CA)	D	D^2	10.53	35.39	40.91	5499.84	5687.74	20269.3	702	723	2554.96	196
$g(D^2H, WD, CA)$	D^2	D^2	−6.07	35.81	44.41	−18.38	62.13	85.13	−4.9	27.79	33.37	199
$g(D^2HW, CA)$	D^2	D^2	−3.46	35.1	43.08	−22.34	59.03	77.9	−4.07	26.48	31.88	200

Selected best models are given in bold.

carpaceae family in the DF. All parameter estimates for the system of equations were significant at 0.03 level of significance and all model components in the system of equations had Adj. R^2 values greater than 0.90 (Table 5).

3.3. Evergreen Broadleaf forest

For the EBLF, the $AGB = f(D^2H, WD, CA)$ model form was the only form not to converge (Table 3). Most model forms resulted in positive PBias with the exception of $AGB = f(D, CA)$ and $AGB = f(D^2H)$, which overestimated AGB and some of the highest RMSPE values. The model form $f(D)$ had the lowest PBias but the second highest RMSPE. Model forms $f(D^2H, WD)$ and $f(D^2HW)$ had low PBias with substantially better MAPE and RMSPE than $f(D)$. As $AGB = f(D^2HW)$ had lower MAPE and RMSPE with fewer parameters requiring estimation than $f(D^2H, WD)$, it was selected as the best overall AGB model form outside of a system of equations.

Validation statistics for the system of equations based on the selected AGB model form are shown in Table 7. While the BGB model form *g(D, H, CA)* resulted in the most extreme validation statistics for BGB and TB, all systems of equations investigated had poor validation statistics for the BGB component and overestimated BGB. Additionally, all systems underestimated AGB and most underestimated TB.

With the exception of *g(D, H, CA)* validation statistics for TB were very similar between the systems of equations. The BGB model form *g(D, WD)* resulted in the lowest MAPE and RMSPE for TB. The addition of H and CA to this model form resulted in the lowest PBias, but increased MAPE and RMSPE. The simplest BGB model form *g(D)* resulted in similar validation statistics to *g (D, WD)* but with less parameters requiring estimation. Therefore, the system of equations with $BGB = g(D)$ was selected as the best preforming model for the EBLF.

While BGB validation statistics were poor and AGB statistics were suboptimal they were similar to the results from other systems and had some of the lower values for BGB and AGB RMSPE. Additionally, once the selected system was fit with the entire data set, AGB and BGB model components had Adj. R^2 of 0.9530 and 0.7219, respectively, and resulted in an Adj. R^2 of 0.9766 for TB (Table 5). All parameter estimates for the system of equations were significant at 0.02 level.

3.4. Need for family-specific versus forest type equations

For the fourteen model forms fit to directly estimate TB in the DF, ten models showed the Dipterocarpaceae indicator parameter to be significant at the 0.05 level, and twelve of the models found it significant at the 0.1 level. The model form $TB = h(D^2H, WD, CA)$

Table 7
Validation statistics for different system of equations involving an AGB model form of *AGB = f(D²HW)* and different model forms for BGB in the EBLF of Viet Nam. Validation statistics for AGB, BGB, and TB include PBias, MAPE, and RMSPE, as well as the number of time models converged in the 200 simulations (C).

BGB model form	Weight		AGB			BGB			TB			C
	BGB	TB	PBias	MAPE	RMSPE	PBias	MAPE	RMSPE	PBias	MAPE	RMSPE	
g(D)	***D***	***D²***	**27.68**	**37.09**	**42.99**	**−111.44**	**122.14**	**158.26**	**9.97**	**19.92**	**25.58**	**195**
g(D, H)	*D*	*D²*	27.93	37.33	43.16	−116.69	128.75	172.79	8.87	21.15	27.44	196
g(D²H)	*D²*	*D²*	29.27	38.82	44.66	−123.27	132.16	165.42	9.9	21.65	27.99	200
g(D, WD)	*D*	*D²*	26.14	36.53	42.78	−111.95	120.61	153.79	8.64	19.49	25.27	200
g(D, CA)	*D*	*D²*	28.04	37.46	43.26	−105.84	119.8	157.74	11.08	20.9	26.59	197
g(D, H, WD)	*D*	*D²*	26.57	36.89	43.1	−119.97	129.97	170.92	7.32	20.51	26.65	200
g(D²H, WD)	*D²*	*D²*	29.95	39.1	44.87	−138.5	143.84	176.09	8.36	21.1	27.24	195
g(D²HW)	*D²*	*D²*	29.2	38.72	44.57	−135.56	142.84	173.96	8.11	20.94	27.07	200
g(D, H, CA)	*D*	*D*	26.54	36.93	43.22	**	*	*	**	*	*	200
g(D²H, CA)	*D²*	*D²*	28.38	37.99	44.01	−122.7	140.45	177.88	9.37	20.7	27.19	200
g(D, WD, CA)	*D*	*D²*	26.76	37.09	43.26	−108.75	117.9	153.81	9.64	20.46	26.26	200
g(D, H, WD, CA)	*D*	*D²*	25.86	36.3	42.7	−125.91	138.5	183.9	5.82	20.07	26.72	199
g(D²H, WD, CA)	*D²*	*D²*	28.05	37.78	43.77	−131.97	146.5	181.26	7.81	19.83	26.16	199
g(D²HW, CA)	*D²*	*D²*	28.36	38.05	44.07	−132.65	144.41	178.47	7.91	19.93	26.32	200

Selected best models are given in bold.
* Value of $x > 10^{19}$.
** Value of $x < -10^{19}$.

did not converge, similar to the other model form results when directly modelling ABG (Table 3).

4. Discussion

4.1. Developed models for total biomass

In this study we compared weighted nonlinear systems of equations for estimating AGB, BGB, and TB for two forest types and one plant family. All three systems of equations developed in this study incorporated an AGB model form that had the D^2HW variable as a predictor and a simple BGB model from with either D^2H or D as the sole predictor variable. The inclusion of the D^2HW predictor in the model forms for AGB agrees with the view that H and WD in addition to D, are influential predictors of AGB in tropical forests. However, for BGB model forms, while at times the addition of WD or CA improved validation statistics, improvements were not substantial enough to outweigh the benefit of more simple and concise model choices.

The system of equations developed for the DF and Dipterocarpaceae in the DF resulted in substantially better validation statistics for the BGB model component than that of the EBLF. This could be due to the diversity of family and species with in the respective forest types; that being that the DF has lower diversity with fewer dominant species or plant families than the EBLF.

Based on the frequency with which an indicator parameter for the Dipterocarpaceae was significant across the model forms, there appears to be a need for a separate model for the Dipterocarpaceae family in the DF. This finding is further supported by differences in the final model form for the DF and Dipterocarpaceae in the DF. This suggests that there is added benefit to developing family-specific equations over forest type equations when sufficient data exists. Although some validation statistics were moderately similar, most AGB model forms between the DF and Dipterocarpaceae in the DF were dissimilar.

For additional applicability, single-entry D-only weighted nonlinear systems of equations were fit for the DF, Dipterocarpaceae in the DF, and EBLF (Table 8). Although some of the D-only models' parameter estimates are not significant at 0.0001 (all estimates from models in Table 5 are), they are at least significant to the 0.05 level. For the DF and EBLF, better TB and AGB root mean square error (RMSE) and Adj. R^2 are observed in the models from Table 5. However, the use of D-only equations for the Dipterocarpaceae in the DF resulted in lower RMSE and higher Adj. R^2 then the system of equations based off of the best preforming AGB model form (Table 5).

4.2. Root biomass

In a recent review of BGB estimation in SE Asia, Yuen et al. (2013) highlighted the increased uncertainty of methods such as allometric relationships, soil cores, and soil pits over root excavation. Only 10% of studies reporting on BGB used data derived from total root excavation methods (Yuen et al., 2013). While this study is unique for its sample size given the method of whole root excavation, we focused on coarse root biomass and did not attempt to sample fine root biomass.

Fine roots play an important role in annual carbon turn over and have been estimated to contribute 33% of global annual net primary production and 40% of total ecosystem production (Jackson et al., 1997; Vogt et al., 1996). However, above-ground components generally contribution much more to the total biomass of a stand than that of the root biomass (Vogt et al., 1996), and fine roots may contribute less than 2% of an ecosystem's total biomass (Vogt et al., 1996). Therefore, while the biomass estimates from the models in the study will likely have a positive bias, it is likely only a slight underestimation.

4.3. Future directions

As generic multi-species models may fail to take advantage of additional information related to structural differences between tree species, the feasibility of family groups or functional species groups are important areas and merit detailed investigation. In our study only the Dipterocarpaceae family had a large enough sample size ($n = 65$) to enable both model fitting and validation by family group. However, it is suspected that WD can act as a surrogate for broader groupings of structurally similar species (Chave et al., 2005, 2009; Iida et al., 2012; Nam et al., 2016; Huy et al., 2016a, 2016b).

Another area requiring attention centres on data collection and what data to use. As collecting AGB measurements is much easier than BGB measurements, it is possible that for the same stand some trees will only have AGB measurements recorded while others may have both AGB and BGB recorded. What is to be done with the sample trees on which only AGB was recorded? Can estimation be informed of diversity within a stand or forest type by

Table 8
Number of trees (N), parameter estimates and approximate standard errors, RMSE, and Adj. R^2 for modelling TB as a system of equations with AGB and BGB components by forest type grouping.

Forest type (N)	Model form	Weight	Parameter	Estimate ± Approx. SE	RMSE	Adj. R^2
DF (105)	*AGB = f(D)*	*D*	a_1^{**}	0.024714 ± 0.00657	28.3380	0.9564
			b_1^{**}	2.87681 ± 0.0744		
	BGB = g(D)	*D*	a_2^{*}	0.024857 ± 0.00896	7.7835	0.8847
			b_2^{**}	2.33086 ± 0.1025		
	$TB = f(\cdot) + g(\cdot)$	*D*	...	...	35.4647	0.9493
Dipterocarpaceae in the DF (65)	*AGB = f(D)*	*D*	a_1^{**}	0.027894 ± 0.00458	15.3496	0.9913
			b_1^{**}	2.832982 ± 0.0456		
	BGB = g(D)	*D*	a_2^{*}	0.030474 ± 0.0139	8.4392	0.9048
			b_2^{**}	2.297503 ± 0.1283		
	$TB = f(\cdot) + g(\cdot)$	*D*	...	...	18.2986	0.9908
EBLF (70)	*AGB = f(D)*	*D*	a_1^{*}	0.012857 ± 0.00576	22.4542	0.8888
			b_1^{**}	3.205086 ± 0.1413		
	BGB = g(D)	*D*	a_2^{*}	0.07565 ± 0.0368	5.6049	0.7686
			b_2^{**}	2.033938 ± 0.1615		
	$TB = f(\cdot) + g(\cdot)$	*D*	...	...	23.2199	0.9089

* Parameters significant at p-value < 0.05.
** Parameters significant at p-value < 0.001.

weighting trees on which both AGB and BGB is measured by trees within the same stand on which only AGB is recorded?

Additionally, it is common that multiple sample trees for biomass might come from the same plot or set of plots. Currently biomass models do not account for the spatial variation within a forest type or the spatial correlation between trees sampled within the same plot. Is there a need for such a consideration in highly diverse stands such as the tropical forests of SE Asia? While the need still exists for more localized AGB and BGB models, these and other questions in modelling total biomass merit attention.

5. Conclusion

This study represents a first attempt at quantifying total tree biomass as a simultaneously fit system of weighted nonlinear equations in Dipterocarp and Evergreen Broadleaf forests of Viet Nam. We found the combination variable D^2HW to be an important predictor in the AGB model component for all the developed system of equations. Furthermore, we found that modelling the BGB component as a function of simply D or D^2H resulted in comparable if not the best validation statistics for TB. Model fit and validation statistics indicate that all three of the systems of equations developed in this study will contribute to the accurate estimation of total biomass in these forest types.

The allometric equations will be useful to forest practitioners and modellers interested in the assessment of total and proportional above or below ground biomass for carbon accounting and for developing REDD+ programs or projects in tropical forests. The allometric equations resulting from this research are applicable to areas in tropical forests where similar climate, soils, and vegetation associations may be found in relation to the study area. Applying them in other parts of tropical forests with similar species and biophysical attributes would help to validate model accuracy.

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References

Basuki, T.M., Van Lake, P.E., Skidmore, A.K., Hussin, Y.A., 2009. Allometric equations for estimating the above-ground biomass in the tropical lowland Dipterocarp forests. For. Ecol. Manage. 257 (2009), 1684–1694. http://dx.doi.org/10.1016/j.foreco.2009.01.027.

Brandeis, T.J., Delaney, M., Parresol, B.R., Royer, L., 2006. Development of equations for predicting Puerto Rican subtropical dry forest biomass and volume. For. Ecol. Manage. 233, 133–142.

Brown, S., 1997. Estimating biomass and biomass change of tropical forests: A Primer. FAO Forestry paper – 134. ISBN 92-5-103955-0. Available on-line: <http://www.fao.org/docrep/w4095e/w4095e00.htm>.

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Folster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Rier, B., Yamakura, T., 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145, 87–99. http://dx.doi.org/10.1007/s00442-005-0100-x.

Chave, J., Coomes, D., Jansen, S., Lewis, S.L., Swenson, N.G., Zanne, A.E., 2009. Towards a worldwide wood economic spectrum. Ecol. Lett. 12, 351–366. http://dx.doi.org/10.1111/j.1461-0248.2009.01285.x.

Chave, J., Mechain, M.R., Burquez, A., Chidumayo, E., Colgan, M.S., Delitti, W.B.C., Duque, A., Eid, T., Fearnside, P.M., Goodman, R.C., Henry, M., Yrrizar, A.M., Mugasha, W.A., Mullerlandau, H.C., Mencuccini, M., Nelson, B.W., Ngomanda, A., Nogueira, E.M., Malavassi, E.O., Pelissier, R., Ploton, P., Ryan, C.M., Saldarriaga, J. G., Vieilledent, G., 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Glob. Change Biol. 20, 3177–3190. http://dx.doi.org/10.1111/gcb.12629.

Dietz, J., Kuyah, S., 2011. Guidelines for Establishing Regional Allometric Equations for Biomass Estimation Through Destructive Sampling. World Agroforestry Center (ICRAF), Nairobi. Protocol CBP 1.3.

Henry, M., Besnard, A., Asante, W.A., Eshun, J., Adu-Bredu, S., Valentini, R., Bernoux, M., Saint-Andre, L., 2010. Wood density, phytomass variations within and among trees, and allometric equations in a tropical rainforest of Africa. For. Ecol. Manage. 260, 1375–1388. http://dx.doi.org/10.1016/j.foreco.2010.07.040.

Hertel, D., Moser, G., Culmsee, H., Erasmi, S., Horna, V., Schuldt, B., Leuschner, C.H., 2009. Below-and above-ground biomass and net primary production in a paleotropical natural forest (Sulawesi, Indonesia) as compared to neotropical forests. For. Ecol. Manage. 258 (9), 1904–1912. http://dx.doi.org/10.1016/j.foreco.2009.07.019.

Huy, B., Poudel, K.P., Temesgen, H., 2016a. Aboveground biomass equations for evergreen broadleaf forests in South Central Coastal ecoregion of Viet Nam: selection of eco-regional or pantropical models. For. Ecol. Manage. 376, 276–283.

Huy, B., Poudel, K.P., Kralicek, K., Hung, N.D., Khoa, P.V., Phuong, V.T., Temesgen, H., 2016b. Allometric equations for estimating tree aboveground biomass in Tropical Dipterocarp Forests of Vietnam. Forests 7 (180), 1–19. http://dx.doi.org/10.1016/j.foreco.2016.06.031.

Iida, Y., Poorter, L., Sterck, F.J., Kassim, A.R., Kubo, T., Potts, M.D., Kohyama, T.S., 2012. Wood density explains architectural differentiation across 145 co-occurring tropical tree species. Funct. Ecol. 26, 274–282. http://dx.doi.org/10.1111/j.1365-2435.2011.01921.x.

IPCC (Intergovernmental Panel on Climate Change), 2003. IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry. In: Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F. (Eds.), Prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan.

Jackson, R.B., Mooney, H.A., Schulze, E.-D., 1997. Aglobal budget for fine root biomass, surface area, and nutrient contents. Proc. Natl. Acad. Sci. USA 94, 7362–7366 <http://www.jstor.org/stable/4221432>.

Kenzo, T., Furutani, R., Hattori, D., Kendawang, J.J., Tanaka, S., Sakurai, K., Ninomiya, I., 2009a. Allometric equations for accurate estimation of above-ground biomass in logged-over tropical rainforests in Sarawak, Malaysia. J. For. Res. 14, 365–372. http://dx.doi.org/10.1007/s10310-10009-10149-10311.

Kenzo, T., Ichie, T., Hattori, D., Itioka, T., Handa, C., Ohkubo, T., Kendawang, J.J., Nakamura, M., Sakaguchi, M., Takahashi, N., Okamoto, M., 2009b. Development of allometric relationships for accurate estimation of above-and below-ground biomass in tropical secondary forests in Sarawak, Malaysia. J. Trop. Ecol. 25 (04), 371–386. http://dx.doi.org/10.1017/S0266467409006129.

Lambert, M.-C., Ung, C.-H., Raulier, F., 2005. Canadian national tree aboveground biomass equations. Can. J. For. Res. 35, 1996–2018. http://dx.doi.org/10.1139/x05-112.

Nam, V.T., van Kuijk, M., Anten, N.P.R., 2016. Allometric equations for aboveground and belowground biomass estimations in an evergreen forest in Vietnam. PLoS ONE 11 (6), e0156827. http://dx.doi.org/10.1371/journal.pone.0156827.

Navar, J., 2009. Allometric equations for tree species and carbon stocks for forests of northwestern Mexico. For. Ecol. Manage. 257, 427.

Parresol, B.R., 2001. Additivity of nonlinear biomass equations. Can. J. For. Res. 31 (5), 865–878.

Phuong, V.T., Linh, N.T.M., 2011. Final Report on Forest Ecological Stratification in Vietnam. UN-REDD Programme, Ha Noi, Viet Nam.

Picard, N., Rutishauser, E., Ploton, P., Ngomanda, A., Henry, M., 2015. Should tree biomass allometry be restricted to power models? For. Ecol. Manage. 353, 156–163. http://dx.doi.org/10.1016/j.foreco.2015.05.035.

Poudel, K.P., Temesgen, H., 2016a. Methods for estimating aboveground biomass and its components for Douglas-fir and lodgepole pine trees. Can. J. For. Res. 46 (1), 77–87.

Poudel, K.P., Temesgen, H., 2016b. Developing biomass equations for Western hemlock and red alder trees in Western Oregon forests. Forests 7 (4), 88. http://dx.doi.org/10.3390/f7040088.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

Ritchie, M.W., Zhang, J., Hamilton, T.A., 2013. Aboveground tree biomass for Pinus ponderosa in northeastern California. Forests 4 (1), 179–196.

SAS Institute Inc., Copyright © 2013. SAS System for Windows. Version 9.4. SAS Institute Inc., Cary, North Carolina.

Sola, G., Inoguchi, A., Garcia-Perez, J., Donegan, E., Birigazzi, L., Henry, M., 2014. Allometric equations at national scale for tree biomass assessment in Viet Nam. Context, methodology and summary of the results, UN-REDD Programme, Ha Noi, Viet Nam.

Temesgen, H., Affleck, D., Poudel, K., Gray, A., Sessions, J., 2015. A review of the challenges and opportunities in estimating above ground forest biomass using tree-level models. Scandinav. J. For. 30 (4), 326–335. http://dx.doi.org/10.1080/02827581.2015.1012114.

Vogt, K.A., Vogt, D.J., Palmiotto, P.A., Boon, P., O'Hara, J., Asbjornsen, H., 1996. Review of root dynamics in forest ecosystems grouped by climate, climatic forest type and species. Plant Soil 187, 159–219. http://dx.doi.org/10.1007/BF00017088.

Yuen, J.Q., Ziegler, A.D., Webb, E.L., Ryan, C.M., 2013. Uncertainty in below-ground carbon biomass for major land covers in Southeast Asia. For. Ecol. Manage. 310, 915–926. http://dx.doi.org/10.1016/j.foreco.2013.09.042.

Zhao, D.H., Kane, M., Markewitz, D., Teskey, R., Clutter, M., 2015. Additive tree biomass equations for midrotation loblolly pine plantations. For. Sci. 61, 613–623.

Zhao, D., Kane, M., Teskey, R., Markewitz, D., 2016. Modeling aboveground biomass components and volume-to-weight conversion ratios for loblolly pine trees. For. Sci. 62, 463–473.

Ziegler, A.D., Phelps, J., Yuen, J.Q., Webb, E.L., Lawrence, D., Fox, J.M., Bruun, T.B., Leisz, S.J., Ryan, C.M., Dressler, W., Mertz, O., 2012. Carbon outcomes of major land-cover transitions in SE Asia: great uncertainties and REDD+ policy implications. Glob. Change Biol. 18 (10), 3087–3099. DOI 0.1111/j.1365-2486.2012.02747.x.