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Allometric Equations for Tropical Seasonal Deciduous Forests in Cambodia: A Method of Estimating Belowground Tree Biomass with Reduced Sampling Loss of Roots

Yukako MONDA[1, 7]*, Eriko ITO[2], Yoshiyuki KIYONO[3], Tamotsu SATO[4], Jumpei TORIYAMA[1], Heng SOKH[5], Sophal CHANN[5], Bora TITH[5], Samkol KETH[5], Op PHALLAPHEARAOTH[5] and Soukanh BOUNTHABANDID[6]

[1] Bureau of Climate Change, Forestry and Forest Products Research Institute (FFPRI) (Tsukuba, Ibaraki 305-8687, Japan)
[2] Hokkaido Regional Research Center, FFPRI (Sapporo, Hokkaido 062-8516, Japan)
[3] Principal Research Coordinator, FFPRI (Tsukuba, Ibaraki 305-8687, Japan)
[4] Department of Forest Vegetation, FFPRI (Tsukuba, Ibaraki 305-8687, Japan)
[5] Forestry Administration, Cambodia (Khann Daun Penh, Phnom Penh, Cambodia)
[6] Department of Forestry, Lao PDR (Chanthabouly District, Vientiane, Lao PDR)

Abstract

There is an urgent need to estimate the biomass of tropical seasonal forests in central Indochina, which have suffered from deforestation and degradation. However, allometric equations specific to such forests are limited. In this study, we destructively sampled 28 trees in a deciduous forest in Kratie Province, Cambodia, and developed new allometric equations for estimating the tree-level biomass of aboveground woody parts (trunk + branches), leaves, total aboveground parts (trunk + branches + leaves), and that of belowground parts (BGB). The sampling of belowground parts is usually very laborious and time-consuming, and entails inevitable root loss during excavation. Thus, it is difficult to accurately quantify tree-level BGB, especially for large trees. We used a new sampling method (called the mound method) to reduce the sampling loss of BGB. The percentage of BGB sampling loss (ratio of sampling loss estimated by the mound method to total BGB) averaged 28.9%. Our models estimated the stand-level biomass of a deciduous dipterocarp forest in Kratie to be 81.9 ± 45.1 Mg ha^{-1}. The allometric equations and tree-level biomass data presented here will support activities related to REDD+.

Discipline: Forestry and forest products
Additional key words: deciduous dipterocarp forest, destructive sampling, forest biomass estimation, REDD+, root system

Introduction

The tropical seasonal forest is a major type of vegetation in Cambodia, Laos, and Myanmar, where serious deforestation has occurred (FAO 2010). Appropriate and simple methods of estimating forest biomass, such as allometric equations, are urgently needed for accurate estimates to support initiatives such as REDD+ ("Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries": https://unfccc.int/methods/redd/methodological_guidance/items/4123.php). There are two main types of tropical seasonal forest: evergreen and deciduous. In

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Present address:
[7] Graduate School of Agriculture, Kyoto University (Kyoto, Kyoto 606-8502, Japan)
*Corresponding author: e-mail monda.yukako.2m@kyoto-u.ac.jp
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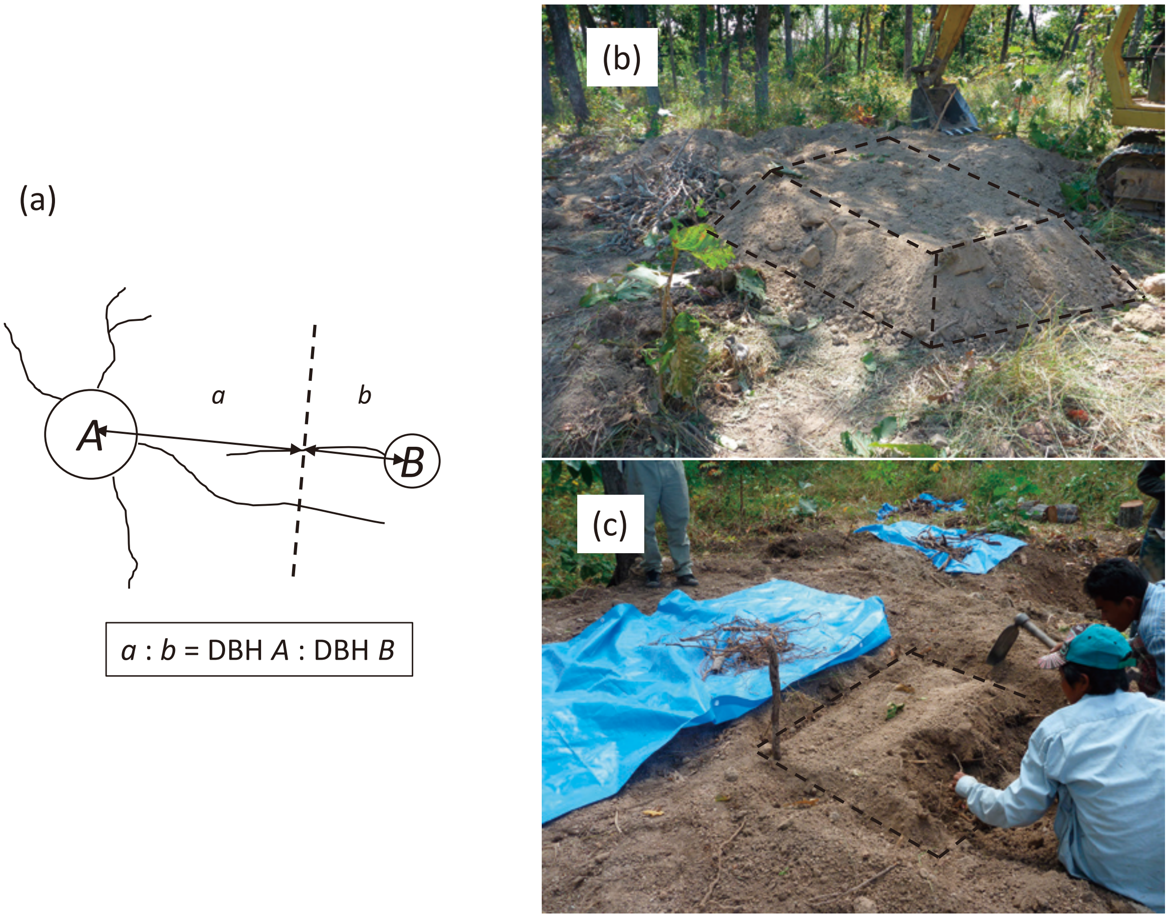

Fig. 1. Sampling of belowground biomass using the mound method. (a) Determination of roots to be sampled from target tree A when the roots overlap those of tree B of the same species. (b) Creating the mound from the excavated soil. The broken lines indicate the shape of the mound. (c) Manual collection of root samples from a sampling block within the mound.

Cambodia, most deciduous forests are dry dipterocarp forests—the main type of forest in central Indochina's dry forest region (Tani et al. 2007). Deciduous forests are categorized as a deciduous dipterocarp forest (DDF) or a mixed deciduous forest. In this study, we focused on a DDF in Cambodia. The DDFs with an open canopy often experience fire (Ruangpanit 1995).

To accurately estimate forest biomass, it is preferable to develop allometric equations specific to each type of forest. As predictions outside the underlying tree size range may be biased (Molto et al. 2013), it is important to cover the entire tree size class of a target forest for developing allometric equations. To estimate aboveground biomass (AGB), Hozumi et al. (1969) measured biomass in an evergreen forest in Cambodia that included large trees. However, only Ogino et al. (1967) in Thailand and Khun et al. (2012) in upland Cambodia have assessed the AGB of deciduous forests, for which they measured relatively small trees.

AGB data have been collected through destructive sampling of a range of tree sizes in tropical forests, and generic allometric equations have been developed (Brown 1997, Chave et al. 2005). However, these equations need coefficients for many variables, such as diameter at breast height (DBH), tree height (H), and wood density (WD), as there are differences in DBH-biomass relations between the datasets of the generic models and specific forest types. Monda et al. (2011) found that Chave's generic models are appropriate for most Cambodian evergreen trees. But whether those models are appropriate for deciduous trees remains moot due to a lack of biomass data for large deciduous trees. Moreover, there has been no study of belowground biomass (BGB) in this type of forest.

BGB data for large trees are particularly limited in the tropics (Niiyama et al. 2010, Lima et al. 2012), primarily because it is difficult and time-consuming to measure roots. Hence, BGB is a major factor of uncertainty in large-scale biomass estimates (Mokany et al. 2006). Even when roots are carefully excavated, it is difficult to avoid the loss of pieces that break off during excavation (Niiyama et al.

Table 1. Destructive sampling data from a deciduous dipterocarp forest in Kratie, Cambodia. DBH: trunk diameter at breast height; H: tree height; –: not measured. Percentage of BGB sampling loss, ratio of BGB sampling loss to total BGB estimated by the mound method (see details in the text).

	DBH	H	Depth of root system	Biomass			Volume of rotted parts		Percentage of BGB sampling loss	Wood density
				Trunk + branches	Leaf	Belowground parts	Aboveground parts	Belowground parts		
Species	(cm)	(m)	(m)	(kg)	(kg)	(kg)	(m^3)	(m^3)	(%)	($g\ cm^{-3}$)
Buchanania lanzan	7.8	6.1	0.6	15.9	–	3.2	–	–	–	0.451
Dipterocarpus tuberculatus	6.8	5.9	0.5	8.3	–	5.4	–	–	–	0.426
Dipterocarpus tuberculatus	12.0	9.4	0.5	46.3	–	16.7	–	–	–	0.503
Dipterocarpus tuberculatus	39.6	13.9	0.7	636.6	–	204.0	0.241	0.089	19.9	0.431
Dipterocarpus tuberculatus	42.0	19.4	0.6	1210.9	–	342.6	0.033	–	19.1	0.599
Heterophragma sulfureum	5.5	3.3	0.6	6.9	0.1	1.7	–	–	–	0.527
Heterophragma sulfureum	10.4	6.6	0.7	18.6	0.7	4.6	–	–	–	0.516
Mitragina rotundifolia	17.5	9.7	0.7	103.6	–	23.3	–	–	–	0.467
Shorea obtusa	10.4	8.3	–	29.4	2.0	7.7	–	–	–	0.665
Shorea obtusa	31.8	15.5	0.3	738.6	32.9	239.6	–	–	19.7	0.596
Shorea obtusa	48.3	27.9	–	1449.6	28.3	435.5	–	–	26.3	0.446
Shorea siamensis	6.6	6.5	0.5	13.9	–	3.0	–	–	–	0.476
Shorea siamensis	9.2	7.1	0.6	17.2	–	6.9	–	–	–	0.590
Shorea siamensis	11.2	7.0	0.3	24.9	–	5.5	–	–	–	0.555
Shorea siamensis	12.8	8.2	0.4	73.3	–	16.0	–	–	–	0.603
Shorea siamensis	14.7	7.3	–	63.8	5.7	14.1	–	–	–	0.472
Shorea siamensis	21.8	15.7	0.6	250.6	–	45.3	–	–	13.8	0.668
Shorea siamensis	27.9	18.1	0.6	437.2	20.1	172.2	–	–	32.4	0.550
Shorea siamensis	57.3	22.1	1.0	1613.3	51.2	675.0	0.107	–	49.5	0.751
Terminalia tomentosa	7.2	6.5	0.4	10.3	–	4.6	–	–	–	0.607
Terminalia tomentosa	11.9	8.9	0.4	59.5	–	18.0	–	–	–	0.619
Terminalia tomentosa	15.7	11.1	0.4	129.9	–	30.0	–	–	–	0.748
Terminalia tomentosa	19.3	10.4	0.5	171.2	–	44.0	–	–	–	0.733
Terminalia tomentosa	21.4	11.9	0.5	153.9	–	42.5	–	–	–	0.670
Terminalia tomentosa	21.8	10.1	0.5	134.4	–	38.7	0.002	–	–	0.614
Terminalia tomentosa	25.7	17.6	0.9	416.1	14.7	193.7	–	–	57.7	0.763
Terminalia tomentosa	42.0	22.6	–	805.9	7.6	279.8	–	–	29.5	0.601
Terminalia tomentosa	50.0	23.5	1.2	2086.9	41.9	302.2	–	–	21.3	0.698

2010, Brassard et al. 2011). And ignoring these sampling losses in the development of allometric equations would result in underestimating BGB, particularly that of large trees (Niklas 2005). Therefore, an appropriate and simple method of reducing BGB sampling losses is required.

The objective of this study was to develop allometric equations for estimating the biomass of aboveground woody parts (trunk + branches), leaves, AGB (trunk + branches + leaves), and BGB of trees in a DDF in Cambodia. We used a new simple method to reduce BGB sampling loss (called the mound method) in the sampling of roots. By using the allometric equations developed from the data, we estimated the stand-level biomass of a deciduous forest in Cambodia.

Materials and methods

1. Study site

We conducted our study in a DDF near the Kratie meteorological observation tower (12°55′15.10″N, 106°11′9.72″E) in Kratie Province, Cambodia. The mean annual rainfall from 1994 to 2004 was 1731 mm (NIS 2006), with a six-month dry season from November to April. The landscape consists of flat terraced land. Tertiary and quaternary sedimentary rocks underlie much of the forest (Toriyama et al. 2010), which has plinthic hydromorphic soil. The dominant species at the study site are the deciduous dipterocarps *Dipterocarpus tuberculatus, Shorea obtusa, Shorea siamensis, and Terminalia tomentosa* (Tani et al. 2007, Kiyono et al. 2010).

2. Destructive sampling

Destructive sampling was performed in December 2010, February 2011, and November 2011. We selected a total of 28 trees from seven species, with DBH ranging from 5.5 to 57.3 cm and H ranging from 3.3 to 27.9 m (Table 1). We measured the DBH and H of each tree before destructive sampling. The values covered almost the entire ranges of DBH and H reported for typical DDFs in Kratie (Kiyono et al. 2010).

The trees were felled with the aboveground parts being separated into the trunk, branches, and leaves. The trunks were cut by chainsaw into logs 2.0 m in length. The biomass loss by sawdust was ignored. We measured all log diameters with a measuring tape. We also measured the diameters and lengths of any cavities found in the logs. The fresh weights of all branches and leaves were measured in the field with a spring balance. Seventeen trees harvested in the middle of the dry season (in February) were bare of leaves.

We defined the stump and roots with diameters of > 2 mm as the belowground parts. These parts were excavated with a mechanical excavator within an area and depth determined from the presence of roots > 2 mm. If the target and neighboring trees were conspecific, the area was determined from the relative DBH values of the two trees (Fig. 1a). We excluded the roots of other species by color and morphology. The belowground parts were carefully collected from the excavated soil, cleaned, and then weighed (BGB from the excavated soil, kg per tree). We also measured the diameter and length of any cavities found in the stump.

3. The mound method

We used the mound method to estimate the sampling loss of the roots of ten large trees with DBH > 21 cm and H > 13 m (Table 1). First, we made one or two mounds from the soil in which the roots had been collected for the aforementioned sampling for belowground parts (Fig. 1b). To estimate the volume of a mound, we flattened the top and measured the width and height. Then we set sampling blocks in the mound (each 1 m × 1 m × average mound height). When the mound volume was larger than 1.1 m^3, two sampling blocks were set into the mound. The volume of the mounds ranged from 1 to 15 m^3 per tree, and the sampling blocks represented 5.1% to 30.5% of the total volume. All of the roots of the target trees were carefully picked out from each sampling block by hand (Fig. 1c), cleaned, and then weighed. These measurements were then extrapolated to obtain the weight of roots in the entire mound volume (BGB sampling loss, kg per tree). The total BGB was defined as BGB from the excavated soil plus BGB sampling loss. The percentage of BGB sampling loss (%) was defined as the ratio of BGB sampling loss to the total BGB. We used Pearson's correlation between DBH and BGB sampling loss to identify any dependence on tree size.

4. Subsamples

Discs 5-cm thick were cut from the trunk (n = 1-3) to determine dry: fresh weight ratios and WD (g cm^{-3}). Subsamples of branches, leaves, and belowground parts were randomly collected from each tree (branches: 0.06-3.51 kg; leaves: 0.05-1.41 kg; roots: 0.16-8.91 kg). The subsamples were transported to the laboratory, oven-dried at 75°C to a constant weight, and then weighed on an electronic balance. For each sample tree, the dry weights (biomass) of the trunk, branches, leaves, and belowground parts were calculated as the product of their fresh weights and the corresponding dry: fresh weight ratios. WD was calculated as the dry weight of the trunk discs, including the bark, divided by the fresh volume.

5. Development of allometric models

To confirm whether DBH, H, and WD were critical predictor variables for allometric models of biomass, we used stepwise regression with Model 1:

Model 1: $\ln(DW) = a + b \ln(DBH) + c \ln(H) + d \ln(WD)$ (1)

The stepwise regression selected DBH and H as critical predictor variables. Thus, we constructed Models 2 to 5 to estimate biomass as follows:

Model 2: $\ln(DW) = a + e \ln(DBH^2 \times H)$ (2)

Model 3: $\ln(DW) = a + b \ln(DBH) + c \ln(H)$ (3)

Model 4: $\ln(DW) = a + b \ln(DBH)$ (4)

Model 5: $\ln(DW) = a + c \ln(H)$ (5)

where DW is the dry weight (kg) of each component, and a-e are regression coefficients. Before calculating AGB, we used Models 2 to 5 to estimate the tree-level leaf mass (n = 11) and then estimated the leaf mass for the 17 bare trees, which we added to the trunk and branch masses.

Each linear model was back-transformed to a power function form. Because the log-transformation of data causes a bias in biomass estimation (Baskerville 1972), the back-transformed values were multiplied by a correction factor (CF) (Sprugel 1983):

CF= e (^{RSE2}/2),

where RSE is the residual standard error obtained from the model regression. To identify the best-fit models, we used the highest adjusted coefficients of determination (R_{adj}^2) and the lowest Akaike information criterion (AIC) values to evaluate the degree of fit between measured and estimated biomass. All regressions were calculated in R software version 3.2.1 (R Core Team 2015).

6. Biomass model comparisons aboveground and belowground

We compared tree-level AGB and BGB as estimated by the models with predictions by four published models (Table 2), which are allometric equations for a dry evergreen forest in Cambodia (DEF_{Cam}: AGB and BGB; Hozumi et al. 1969) and a deciduous dipterocarp forest in Thailand (DDF_{Thai}: AGB; Ogino et al. 1967), and for a tropical lowland dipterocarp forest in East Kalimantan (LD_{FKal}: AGB; Yamakura et al. 1986) and Pasoh (LDF_{Pasoh}: AGB and BGB, Niiyama et al. 2010).

7. Estimates of stand-level biomass in a deciduous dipterocarp forest

To estimate the biomass of DDFs on a unit area basis by using our best model, we used tree census data from six plots in Kratie Province. The DBH and H of trees with DBH ≥ 5 cm were measured in two plots (20 m × 100 m) by Cambodia's Ministry of the Environment (MoE), and in wildlife sanctuaries and in four plots (50 m × 50 m) by the Forestry Administration of Cambodia (FA).

Results

1. Biomass of sample trees and reduction in root sampling loss by the mound method

The biomass of trunk + branches obtained by destructive sampling ranged from 6.9 to 2086.9 kg per tree (n = 28), leaf biomass from 0.1 to 51.2 kg per tree (n = 11), and BGB from 1.7 to 675.0 kg per tree (Table 1). Four trees had heart rot inside their trunks, and one inside its stump. The volume of these rotted parts accounted for < 2% of woody parts (trunk + stump), except in one tree (27.2%), indicating that heart rot had little effect on individual biomass. WD ranged from 0.426 to 0.763 g cm^{-3}.

The BGB sampling loss estimated by the mound method ranged from 6.3 to 334.2 kg per tree and increased significantly with DBH ($P < 0.05$, $R^2 = 0.419$, $n = 10$). The percentage of BGB sampling loss was 28.9% on average, with a maximum of 57.7% (Table 1).

2. Development of allometric equations and estimate of deciduous dipterocarp forest biomass

For leaf biomass, Model 2 had a higher R_{adj}^2, but a higher AIC value than Model 4 (Table 3). We suspect that the higher AIC value in Model 2 resulted from the small sample size (n = 11). Thus, we selected Model 2 as the best model for leaf biomass. For the biomass of aboveground woody parts, AGB, and BGB, Model 2 had the highest R_{adj}^2 and the lowest AIC values among the four models. Therefore, we also selected Model 2 as the best model for estimating the biomass of aboveground woody parts, AGB, and BGB.

We used these best models and tree census data from the six plots in Kratie Province to calculate the forest biomass per unit area. Estimated stand biomass (AGB + BGB) varied among plots from 32.2 to 158.9 Mg ha^{-1} (Table 4). The MoE plots had larger ABG and BGB than the FA plots. Among large trees (DBH > 30 cm), the MoE plots also had greater tree density (ha^{-1}) than the FA plots. The estimated stand biomass values averaged 64.8 ± 36.3 Mg ha^{-1} for AGB and 17.1 ± 8.9 Mg ha^{-1} for BGB.

3. Comparison of AGB and BGB among models

We compared tree-level AGB estimated by Model 2 with values predicted by the four earlier models (Table 2) in two ways. In one comparison, we used the values of DBH and H from our sample trees (Table 1) to calculate AGB (Fig. 2a). In the other comparison, we used a given DBH and the corresponding value of H that was predicted from the DBH-H relationship presented in each paper to calculate AGB by each model (Fig. 2b). When the actual H was used, the AGB predicted by the DEF_{Cam} and LDF_{Kal} models was close to that predicted by Model 2, but the AGB predicted by the DDF_{Thai} model was smaller, and that by the LDF_{Pasoh} model was larger than that of Model 2 (Fig. 2a). For example, for the largest sampled tree (DBH = 57 cm), the DEF_{Cam} AGB was 0.97 times, the LDF_{Kal} AGB was 1.00 times, the DDF_{Thai} AGB was 0.84 times, and the LDF_{Pasoh} AGB was 1.42 times larger than those our that of Model 2. When H was calculated for each forest type, the DDF_{Thai} AGB was smaller, and the DEF_{Cam}, LDF_{Kal} and LDF_{Pasoh} AGBs were all larger than those of Model 2 (Fig. 2b). For example, for the largest sampled tree, the DDF_{Thai} AGB was 0.69 times, the DEF_{Cam} AGB was 1.22 times, the LDF_{Kal} AGB was 1.89 times, and the LDF_{Pasoh} AGB was 2.29 times the AGB of Model 2.

We compared the tree-level BGB estimated by Model 2 with values predicted by two earlier models that included BGB (Table 2). The DEF_{Cam} BGB was smaller but the LDF_{Pasoh} BGB was larger than the BGB of Model 2. For the largest sampled tree, the DEF_{Cam} BGB was 0.8 times and the LDF_{Pasoh} BGB was 1.42 times that of Model 2. Even when comparing BGB estimated by models that only included DBH (Model 4, DEF_{Cam}, and LDF_{Pasoh}), a similar trend was seen (Fig. 3).

Table 2. Biomass regression (kg per tree) models compared with our models. DBH: trunk diameter at breast height (cm); H: tree height (m). Equations for each component in Hozumi et al. (1969) include the fresh: dry weight ratio given by the authors (trunk: 0.55; branches: 0.45; leaves: 0.407; BGB: 0.535).

Reference	Biomass component	Model	DBH range (cm)	Site	Forest type
Hozumi et al. (1969)	Stem	$0.072 \times (DBH^2H)^{0.9326} \times 0.55$	1.0-133.2	Koh Kong, Cambodia	Dry evergreen (seasonal) forest
	Branches	$0.01334 \times (DBH^2H)^{1.027} \times 0.45$	1.0-133.2		
	Leaves	$0.031 \times (DBH^2H)^{0.7211} \times 0.407$	1.0-133.2		
	BGB	$0.01369 \times DBH^{2.728} \times 0.535$	5.1-25.8		
Ogino et al. (1967)	Stem	$189 \times ((DBH/100)^2 \times H)^{0.902}$	2.0-23.0	Nakhon Ratchasima, Thailand	Deciduous dipterocarp forest
	Branches	$0.125 \times (\text{stem biomass})^{1.204}$	2.0-23.0		
	1/Leaves	$11.4 / (\text{stem biomass})^{0.9} + 0.172$	2.0-23.0		
Yamakura et al. (1986)	Stem	$2.903 \times 10^{-2} \times (DBH^2H)^{0.9813}$	4.5-130	East Kalimantan, Indonesia	Lowland dipterocarp forest
	Branches	$0.1192 \times (\text{stem biomass (kg)})^{1.059}$	4.5-130		
	Leaves	$9.146 \times 10^{-2} \times (\text{stem + branch biomass (kg)})^{0.7266}$	4.5-130		
Niiyama et al. (2010)	Stem + branches	$0.036 \times (DBH^2H)^{1.01}$	0.5-116.0	Pasoh, Malaysia	Lowland dipterocarp forest
	1/Leaves	$1/(0.108 \times (\text{stem + branch biomass})^{0.75}) + 1/105$	0.5-116.0		
	BGB	$0.023 \times DBH^{2.59}$	0.5-116.0		

Discussion

1. Allometric equations for estimating deciduous dipterocarp forest biomass

We developed allometric equations for estimating the biomass of deciduous dipterocarp forests, based on destructive sampling (including the mound method) conducted in Kratie Province, Cambodia (Table 1). Model 2, which had DBH and H as independent variables, was selected as the best model for both AGB and BGB (Table 3). Chave et al. (2005) concluded that the most important independent variables were DBH, H, WD, and forest type. However, to incorporate WD into biomass estimation, advanced expertise is essential for correct species identification to specify WD as a species-, genus-, or family-level average. Our best models can estimate forest biomass without species identification. Further, when treetops are easily discerned (in DDF, for example), selecting models that include H improves the accuracy of biomass estimates. But when treetops are difficult to discern, selecting models without H can avoid errors in field measurements. Our models (Model 4) only included a single parameter (DBH) as an independent variable, and offer an advantage when only DBH data is available for estimating biomass in other DDFs in Cambodia.

We calculated the forest biomass per unit area using the best models and tree census data from Kratie. Stand average values were 64.8 ± 36.3 Mg ha^{-1} for AGB and 17.1 ± 8.9 Mg ha^{-1} for BGB (Table 4). The biomass of plots in the MoE wildlife sanctuaries were higher than those in the outside sanctuaries (FA plots). The averaged AGB and BGB values of DDF in Cambodia are smaller than those of DEF_{Cam} (means: AGB = 315 Mg ha^{-1}, BGB = 95.6 Mg ha^{-1}; Hozumi et al. 1969) and LDF_{Pasoh} (AGB = 536 Mg ha^{-1}, BGB = 95.9 Mg ha^{-1}; Niiyama et al. 2010). Conversely, the averaged BGB/AGB values of DDF in Cambodia (0.264) are higher than those of DEF_{Cam} (0.171 and 0.204) and LDF_{Pasoh} (0.18).

All models except the DDF_{Thai} and LDF_{Pasoh} models were appropriate for estimating the AGB of deciduous trees in Kratie (Fig. 2a). However, when H was based on the DBH-H relation of each earlier model's specific forest type, AGB was either overestimated or underestimated (Fig. 2b). Thus, there are differences in the DBH-AGB relation between our forest type and other forest types, and the inclusion of H is essential for estimating AGB when using models developed for other forest types. Moreover, LDF_{Pasoh} may also differ in WD from the DDF in Cambodia because AGB in the DDF in Cambodia was still overestimated even when the H was based on the DBH-H relation of LDF_{Pasoh} (Fig. 2a, b). Although the forest type was the same as the DDF in Cambodia, the DDF_{Thai} model underestimated AGB (Fig. 2a, b). This model is based on datasets with low maximum tree sizes. Cambodian deciduous forests have many large trees with DBH values > 30 cm (tree census data from MoE and FA). The data obtained from large trees significantly affect the parameters of allometric regressions (i.e., slope and intercept) and biomass estimates (Kato et al. 1978). Thus, extrapolation from a small-tree dataset likely produces substantial overestimates or underestimates of biomass. Similar trends were seen for BGB estimation. The LDF_{Pasoh} and DEF_{Cam} models overestimated and underestimated BGB even when compared to our Model 4 that only included DBH (Fig. 3). The larger BGB of the DDF in Cambodia may reflect a lower soil water content than DEF_{Cam} (Araki & Ito 2009). Alternatively, there are two possibilities: (1) The DEF_{Cam} model for BGB is based on datasets with low values of maximum tree size, or (2) BGB sampling losses were not considered in development of the DEF_{Cam} model. Further data should be based on BGB sampling methods that reduce sampling losses during excavation.

2. Advantages of the mound method in reducing BGB sampling losses

Niiyama et al. (2010) estimated that BGB sampling losses during excavation amounted to approximately 23% of the total coarse root dry weight in a tropical lowland dipterocarp forest in Pasoh. Our mound method estimated the percentage of BGB sampling losses to be as high as 57.7%, and averaging 28.9% ± 14.2%. As the BGB sampling losses increase with DBH ($P < 0.05$), the mound method can improve the accuracy of BGB estimates for large size classes.

The mound method is suitable for hard soils or gentle slopes where an excavator can work. Excavators are available in most countries and can reduce the time needed for destructive sampling, thereby offsetting the costs of field work. However, in this study, we did not homogenize the soil to ensure an even distribution of roots within the mound soil. The ratio of sampling block volume to mound volume averaged 11.8% with one exception (30.5%). To assess the value of the mound method, it will be necessary to identify the optimum ratio of sampling block volume.

Conclusion

We have developed the first allometric equations for tropical seasonal deciduous forests in Cambodia by using a new BGB sampling method. Because little BGB data is available for tropical seasonal forests, our study contributes substantially to BGB research, particularly for large trees. The allometric equations presented here can accurately estimate both the aboveground and belowground biomass of tropical seasonal deciduous forests in Cambodia, even if only DBH is available (by using Model 4). Therefore, our study will support activities related to REDD+ in Cambodia and neighboring countries in Indochina.

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Table 3. Estimated coefficients and parameters indicating degree of fit for allometric models to estimate biomass in a deciduous dipterocarp forest in Kratie, Cambodia. DBH: trunk diameter at breast height (cm); H: tree height (m); WD: wood density (g cm^{-3}). Adjusted R^2: adjusted coefficient of determination; CF: correction factor; AIC: Akaike information criterion; FI: Furnival's index; ns: not significant; *P < 0.05; **P < 0.01; ***P < 0.001.

Model	*a*	DBH *b*	H *c*	WD *d*	DBH^2 × H *e*	Adjusted R^2	CF	AIC
Aboveground biomass (n = 28)								
Model 1	-2.350	2.035 ***	0.630 *	0.362 ns		0.979	1.032	-123.88
Model 2	-2.710				0.924 ***	0.979	1.032	-125.82
Model 3	-2.655	2.014 ***	0.700 *			0.979	1.036	-124.28
Model 4	-2.438	2.518 ***				0.975	1.039	-125.29
Model 5	-2.855		3.212 ***			0.914	1.141	-107.95
Belowground biomass (n = 28)								
Model 1	-3.904	1.762 ***	1.032 *	0.192 ns		0.964	1.058	-115.91
Model 2	-4.030				0.928 ***	0.967	1.054	-118.81
Model 3	-4.066	1.751 ***	1.069 **			0.965	1.056	-118.34
Model 4	-3.734	2.521 ***				0.956	1.071	-115.07
Model 5	-4.240		3.254 ***			0.918	1.137	-106.32
Aboveground woody parts (stem + branches) (n = 17)								
Model 1	-2.402	2.041 ***	0.632 *	0.370 ns		0.979	1.033	-123.40
Model 2	-2.769				0.927 ***	0.979	1.034	-125.32
Model 3	-2.714	2.019 ***	0.703 *			0.978	1.034	-125.08
Model 4	-2.495	2.526 ***				0.975	1.040	-124.85
Model 5	-2.915		3.222 ***			0.916	1.143	-107.77
Leaf biomass (n = 11)								
Model 2	-5.569				0.849 ***	0.845	1.376	-22.84
Model 3	-5.588	1.654 ***	0.908 ns			0.824	1.441	-22.10
Model 4	-5.655	2.419 ***				0.839	1.391	-24.66
Model 5	-5.056		2.725 ***			0.817	1.462	-23.89

Table 4. Estimates of biomass in six tree census plots in Kratie, Cambodia. MoE: Ministry of the Environment, Cambodia; FA: Forestry Administration, Cambodia.

Plot	Density (tree ha^{-1})	Basal area (m^2 ha^{-1})	Biomass (Mg ha^{-1}) Trunk + branch	Leaf	Aboveground parts	Belowground parts	Total	BGB/AGB	Site
1	705	16.4	84.5	2.2	86.7	21.6	108.3	0.249	MoE plot
2	845	12.1	123.2	3.3	126.5	32.4	158.9	0.256	MoE plot
3	1125	10.5	42.7	1.5	44.2	12.2	56.4	0.277	FA plot
4	624	10.7	54.9	1.7	56.6	15.7	72.3	0.278	FA plot
5	695	9.3	48.0	1.5	49.5	13.8	63.2	0.278	FA plot
6	625	6.1	24.4	0.8	25.3	7.0	32.2	0.276	FA plot
Mean			62.9	1.8	64.8	17.1	81.9	0.264	
SD			35.4	0.8	36.3	8.9	45.1	0.013	

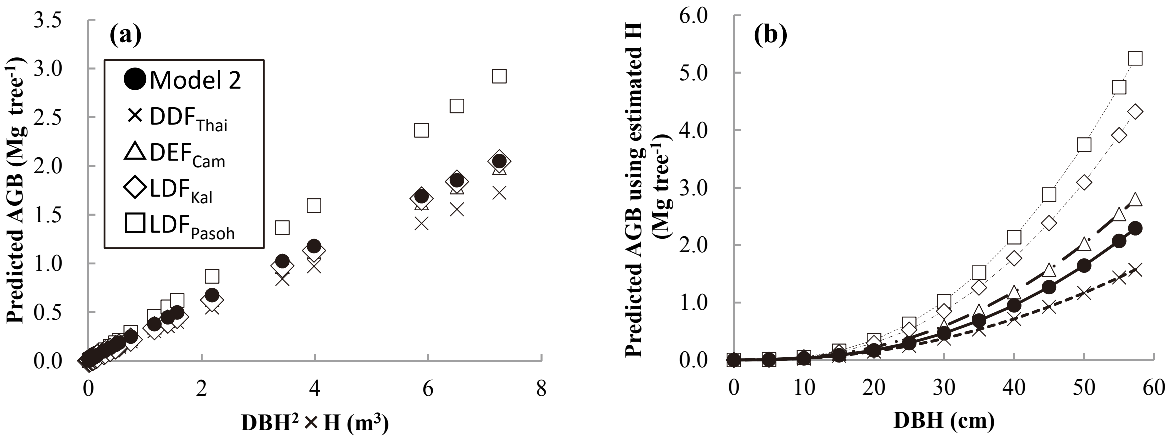

Fig. 2. Comparison of tree level aboveground biomass (AGB) predicted by Model 2 (Table 3) with predictions by the earlier models for other forest types (Table 2). (a) AGB was calculated using DBH and H from our sample trees in Kratie (Table 1). (b) AGB was calculated using a given DBH and the corresponding H that was predicted from the DBH-H relationship presented for each forest type. Model 2: deciduous dipterocarp forest in Cambodia; DDF_{Thai}: deciduous dipterocarp forest in Thailand; DEF_{Cam}: dry evergreen forest in Cambodia; LDF_{Kal}: lowland dipterocarp forest in East Kalimantan; LDF_{Pasoh}: lowland dipterocarp forest in Pasoh.

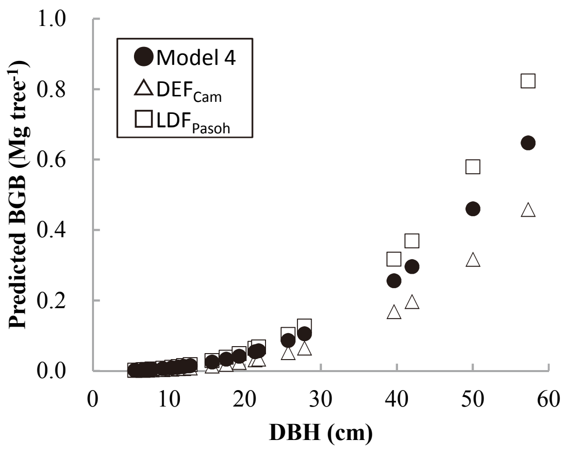

Fig. 3. Comparison of tree-level belowground biomass (BGB) predicted by Model 4 which only included DBH as a predictor variable (Table 3) with predictions by the earlier models for other forest types (Table 2). Model 4: deciduous dipterocarp forest in Cambodia; DEF_{Cam}: dry evergreen forest in Cambodia; LDF_{Pasoh}: lowland dipterocarp forest in Pasoh.

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