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Allometric equations for accurate estimation of forest biomass in tropical logged-over and early successional secondary forests in Sarawak, Malaysia

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Abstract Accurate estimation of biomass in tropical forests is essential to evaluate the base line for nations' carbon storage on–the REDD+ scheme. Presently, allometric equations derived from tropical primary forest trees are usually used to estimate the forest biomass of different forest types, such as primary, logged-over and early successional secondary forests. However, it is uncertain whether these previously developed allometric equations are appropriate for biomass estimation on logged-over and early successional secondary forests, because those forests consist of significantly different species with different structural traits, such as lower wood density compared to primary forest trees, and these traits are generally related to different coefficients of the equations. In this study, we 1) developed allometric equations for logged-over and early successional forests in Sarawak, Malaysia and 2) compared various allometric equations, including those for primary and secondary forests, to evaluate the adequacy of biomass estimation for studied forests. We found that allometric equations developed for the two forest types significantly differ from that for the primary forests and even that for the pan-tropic general models. Moreover, below-ground equations for early successional forest also showed significantly lower biomass estimation than those for primary forest. Therefore, the choice of the biomass estimation models for the tropical logged-over and early successional secondary forests requires careful consideration of their suitability.

Keyword Biomass, Carbon, REDD+, Wood density

Introduction

Determining the allometric relationships for both above- and below-ground biomass of tropical secondary- and logged over- forest trees contributes to the accurate estimation of forest biomass in tropical regions. Presently, allometric equations derived for tropical primary forest trees are generally used to estimate the forest biomass of tropical regions, including not only primary forest but also secondary forest (Brown 1997; Chave et al. 2004, 2005). However, tropical secondary and logged-over forests consist of significantly different tree species with different structural traits, such as low wood density, low tree height and shallow rooting depth, compared to the primary forest trees, and these traits are generally related to variation in the coefficients of the allometric relationships (Chave et al. 2004, 2005). As a result, both above- and below-ground biomass of tropical secondary- and logged over- forest trees may be overestimated. Therefore, determining the allometric relationships of both above- and below-ground biomass for those trees is required for accurate estimation of biomass in the tropical area.

The objectives of this study are (1) to develop the allometric relationships between certain dimensional variables such as tree diameter and plant-part biomass in tropical secondary and logged over- forests in Sarawak, Malaysia and (2) to assess the variation and suitability of the developed allometric relationships through comparison of relationships among previously reported equations derived from tropical primary and/or other forest biomass.

Materials and methods

Study site and plant materials

The study was conducted in a logged-over tropical rainforest in the Sabal Forest Reserve (01°03'N, 110°55'E) and Balai Ringin Protected Forest (00°55'N, 110°43'E), and in an early successional secondary forest in the Niah Forest Reserve (3°39'N, 113°42'E) and the Sungai Liku area located in the Lambir Hills National Park (4°14'N, 114°04'E) in Sarawak, Malaysia (Table 1, Kendawang et al. 2007; Kenzo et al. 2009a, 2009b). All areas have a humid tropical climate. Average temperature is about 25 °C in the study sites. Annual rainfall is 2800–4000 mm. The soil at Sabal had significantly lower nutrient and clay content compared to that at the Balai Ringin site (Table 1). The soil at the Niah site is classified as Typic Kandihumult and is mainly composed of moderately soft grey mudstone and shale (Kendawang et al. 2007). The soil type at the Sungai Liku site is Ultisols (Kenzo et al. 2009b).

The original vegetation at the Sabal site was lowland mixed dipterocarp forest and heath forest (*kerangas*). That of the Balai Ringin site consisted of lowland mixed dipterocarp forest (Kenzo et al. 2015). The forest at both sites has undergone selective logging for commercial use in the past 20 years. Harvested trees were mainly dipterocarp species such as *Shorea* spp. The forest canopy in both sites is almost closed and some of the canopy trees have reached heights of approximately 40 m. The forest mainly consists of late-successional and pioneer tree species belonging to genera such as *Gluta* (Anacardiaceae), *Alstonia* (Apocynaceae), *Santiria* (Burseraceae), *Shorea* (Dipterocarpaceae), *Macaranga* (Euphorbiaceae), *Litsea* (Lauraceae), *Aglaia* (Meliaceae) and *Artocarpus* and *Ficus* (Moraceae).

The original vegetation at the Niah and Sungai Liku sites was also lowland mixed dipterocarp forest. The forest at the Niah site underwent selective logging in the 1980s. At the end of the 1980s, after logging, shifting cultivation was started in the area. Shifting cultivation was conducted only once at the site. We mainly cut down pioneer trees from 4–20 year-old forests after abandonment of shifting cultivation (Kenzo et al. 2007, 2010). We also conducted the study along a gravel road in the Sungai Liku area in Lambir. The road had been built around the 1980s, and many pioneer trees, such as species of *Macaranga* and *Ficus*, covered the roadsides. The forests at

Table 1 Mean total nitrogen (N), available phosphorus (P), clay content, soil texture and elevation of the study sites (Kendawang et al. 2007, Hattori et al. 2013). Data on soil properties are at the A horizon (approx. 0–5 cm from the soil surface). Texture class is as proposed by the International Society of Soil Science.

Site	Altitude (m a.s.l.)	Slope Ave. gradient	N ($g\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Clay (%)	Soil texture
Sabal	60	8°	1.16	4.10	7	Sandy loam
Balai Ringin	90-120	26°	4.13	8.37	77	Heavy clay
Niah	45	8°	1.25	8.73	32	Sandy loam
Sungai Liku	60	5°	1.75	7.99	15-25	Sandy loam

Niah mainly contained pioneer trees such as species of *Macaranga*, *Artocarpus* and *Ficus*. Approximately 50 % of the trees at both the Niah and Sungai Liku sites were *Macaranga* and *Ficus* species (Hattori et al. 2013). The other represented tree species were *Glochidion* spp., *Callicarpa* spp., *Dillenia suffruticosa* and *Endospermum diadenum*. Canopy height varied from 5 to 20 m with stand age. Relative light intensity measured using an illuminance meter (T-10, Konica Minolta, Japan) was approximately 8–10 % (Kenzo et al. 2007).

Biomass measurements for allometric relationships

In total, 30 trees representing 27 species, 22 genera and 16 families were harvested and measured for above-ground parts in logged over forests of the Sabal and Balai Ringin sites (Kenzo et al. 2009a). Individuals with damaged crowns or broken trunks were not considered. Harvested trees ranged from 1.0 to 44.1 cm in diameter at breast height (dbh, 1.3 m) and from 1.5 to 40.0 m in height. All selected species were typical species in both study sites.

In total, 136 trees representing 23 species, 14 genera and eight families were harvested and measured for above-ground parts just before root excavation at the secondary forests of the Niah and Sungai Liku sites (Kenzo et al. 2009b). Harvested trees ranged from 0.1 to 23.0 m in height and from 0.2 to 31.8 cm in diameter at the ground surface. All selected species were typical secondary-forest trees in the area. After harvesting, diameter at breast height (dbh, 1.3 m) and at ground surface (D_0), tree height (H), and leaf and stem fresh weight of all trees were measured.

Root excavation was carried out for 77 of the harvested trees, representing 16 species, 11 genera and seven families (Kenzo et al. 2009b). Excavated trees ranged from 0.1 to 18.6 m in height and from 0.2 to 27.6 cm in diameter at the ground surface. Roots were carefully excavated, using hand tools, from the stump to roots of less than 1–2 mm in diameter. Only live roots, noticeable by their healthy bark, were harvested. The roots were then washed by hand with water. We attempted to harvest all roots, but we should note that not all fine roots could be harvested; small parts, especially ones of less than 2-mm diameter, may be missed. Roots were then divided into small (diameter < 5 mm) and coarse (diameter ≥ 5 mm) roots. Total fresh weight of each tree part was measured in the field and then representative samples were dried in the laboratory to determine moisture content. These samples were oven-dried at 60 ºC for > 72 h until they reached constant mass.

Diameter at breast height (dbh), H (tree height), and ground surface (D_0) were tested as independent variables to estimate biomass. Preliminary analysis of alternative equations indicated

Table 2 Results of regression analyses for predicting plant part biomass of subject trees from dbh and H ($y = ax^b$) using data from all studied individuals in logged-over forests.

Dependent variable (y)	Independent variable (x)	No. of trees	a (± SE)	b (± SE)	Adjusted R^2
Leaf dry biomass (kg)	dbh (cm)	30	0.0442 ± 0.0148	1.67 ± 0.14	0.83
	dbh^2 *H (cm^2 m)	30	0.0346 ± 0.0122	0.57 ± 0.05	0.83
	H (m)	30	0.0215 ± 0.0087	1.81 ± 0.16	0.82
Branch dry biomass (kg)	dbh (cm)	24	0.0124 ± 0.0064	2.48 ± 0.19	0.88
	dbh^2 *H (cm^2 m)	24	0.0101 ± 0.0056	0.83 ± 0.07	0.86
	H (m)	24	0.0069 ± 0.0046	2.53 ± 0.24	0.83
Stem dry biomass (kg)	dbh (cm)	30	0.0822 ± 0.0152	2.48 ± 0.08	0.97
	dbh^2 *H (cm^2 m)	30	0.0567 ± 0.0103	0.85 ± 0.02	0.98
	H (m)	30	0.0274 ± 0.0063	2.69 ± 0.09	0.97
Above-ground biomass (kg)	dbh (cm)	30	0.1525 ± 0.0188	2.34 ± 0.05	0.99
	dbh^2 *H (cm^2 m)	30	0.1083 ± 0.0138	0.80 ± 0.12	0.99
	H (m)	30	0.0558 ± 0.0113	2.53 ± 0.08	0.97

that the allometric equation $y = ax^b$ (where y is biomass (kg), x is dbh or D_0 (cm), and a and b are coefficients estimated by regression) fitted the data best. All regressions were carried out using SPSS ver. 11.5 for Windows (SPSS Japan Inc., Tokyo, Japan).

Results and Discussion

Allometric relationships in the logged-over forests

The developed allometric equations for total above-ground biomass as a function of dbh and H showed high correlation from 0.97 to 0.99 (Table 2, Fig. 1). There was also a relatively high coefficient for the allometric relationships between dbh^{2-} × H and above-ground biomass (0.99, Table 2). In addition, analysis of covariance (ANCOVA) did not show any significant difference ($P > 0.05$) for the allometric equations of total above-ground biomass between study sites (Fig. 1), though these sites showed significantly different soil properties (Table 1). These results indicate that the developed equations can be used to estimate above-ground biomass at the logged-over forests of Sarawak, even in the forests growing on different types of soil nutrients and clay content. We should note that, however, Kenzo et al. (2015) indicated that below-ground biomass, especially the small-root component, was 4-fold larger in Sabal with sandy, nutrient-depleted soil than that in Balai Ringin with nutrient- and clay-rich soil.

On the other hand, allometric relationships for leaf and branch biomass as a function of dbh and H showed a relatively lower correlation coefficient (from 0.82 to 0.88) compared with those for stem and total above-ground biomass (Table 2, Fig. 1). Similar trends have also been reported for leaf biomass in other forest trees (Kira and Shidei 1967; Kenzo et al. 2009b). Relatively large plasticity in the allocation to leaf component with ontogeny and/or environmental conditions such as light, soil nutrients and water may be a cause for variations of the leaf and

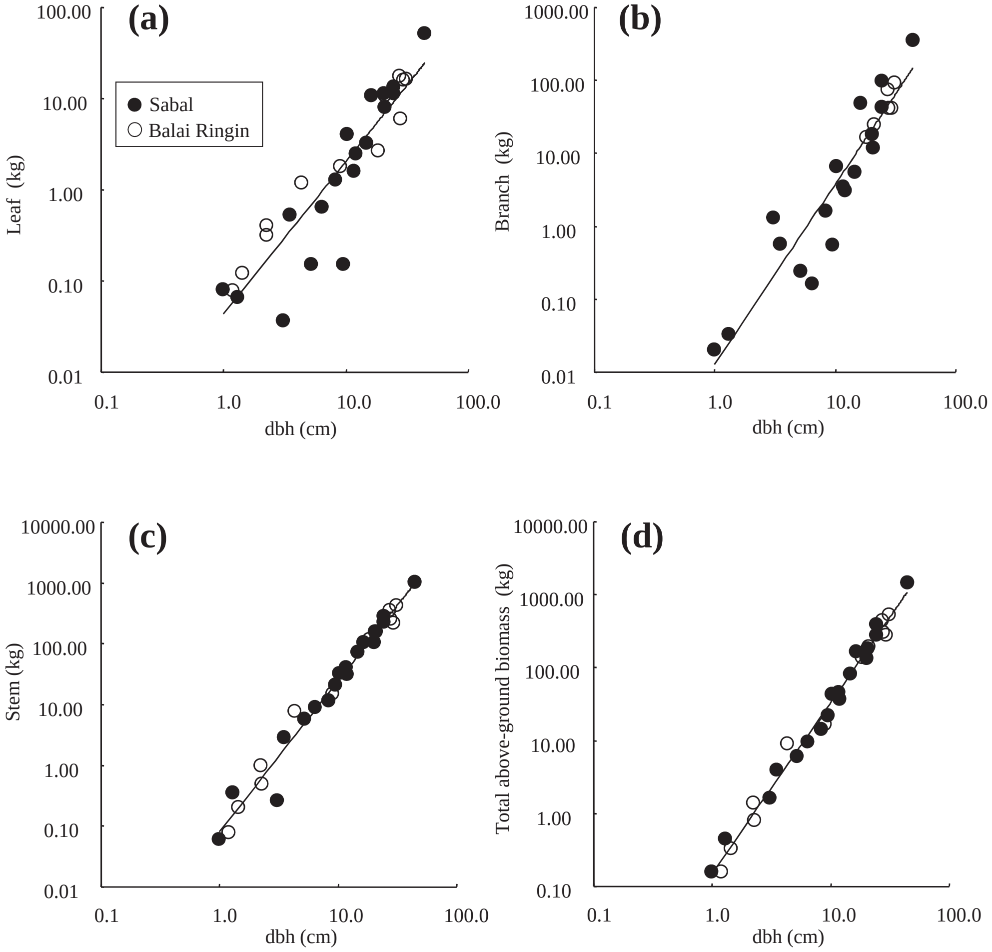

Fig. 1 Allometric relationships between above-ground parts biomass and dbh in logged over forest trees. Leaf biomass (a), branch (b), main stem (c), and total above-ground biomass (d) in relation to dbh, respectively. The regression coefficients are shown in Table 2.

branch allometric relationships (Lambers et al. 1998). In fact, significant interspecific differences in the leaf allometric equation have also been reported for trees in early successional tropical secondary forest trees (Kenzo et al. 2009b).

Allometric relationships in the early successional secondary forests

All allometric relationships for early successional secondary forests also showed a significantly high correlation coefficient with low interspecific differences, except for leaf biomass (Table 3, Fig. 2). A particularly high correlation ($R^2 \geq 0.94$) was found for total root and stem biomass as a function of dbh or D_0. More accurate estimates of both total and small-root biomass were obtained by using D_0 instead of dbh (Table 3, Fig. 2). Analysis of covariance (ANCOVA) did not show any significant effect ($P > 0.05$) of tree species as a predictor variable for the stem, total or small-root biomass estimates, although interspecific differences in stems were found between *Ficus stolonifera* and *Macaranga bancana* when D_0 was used for the function (Fig. 2, Kenzo et al. 2009b). This low interspecific variation in the allometric relationships of stem and total root

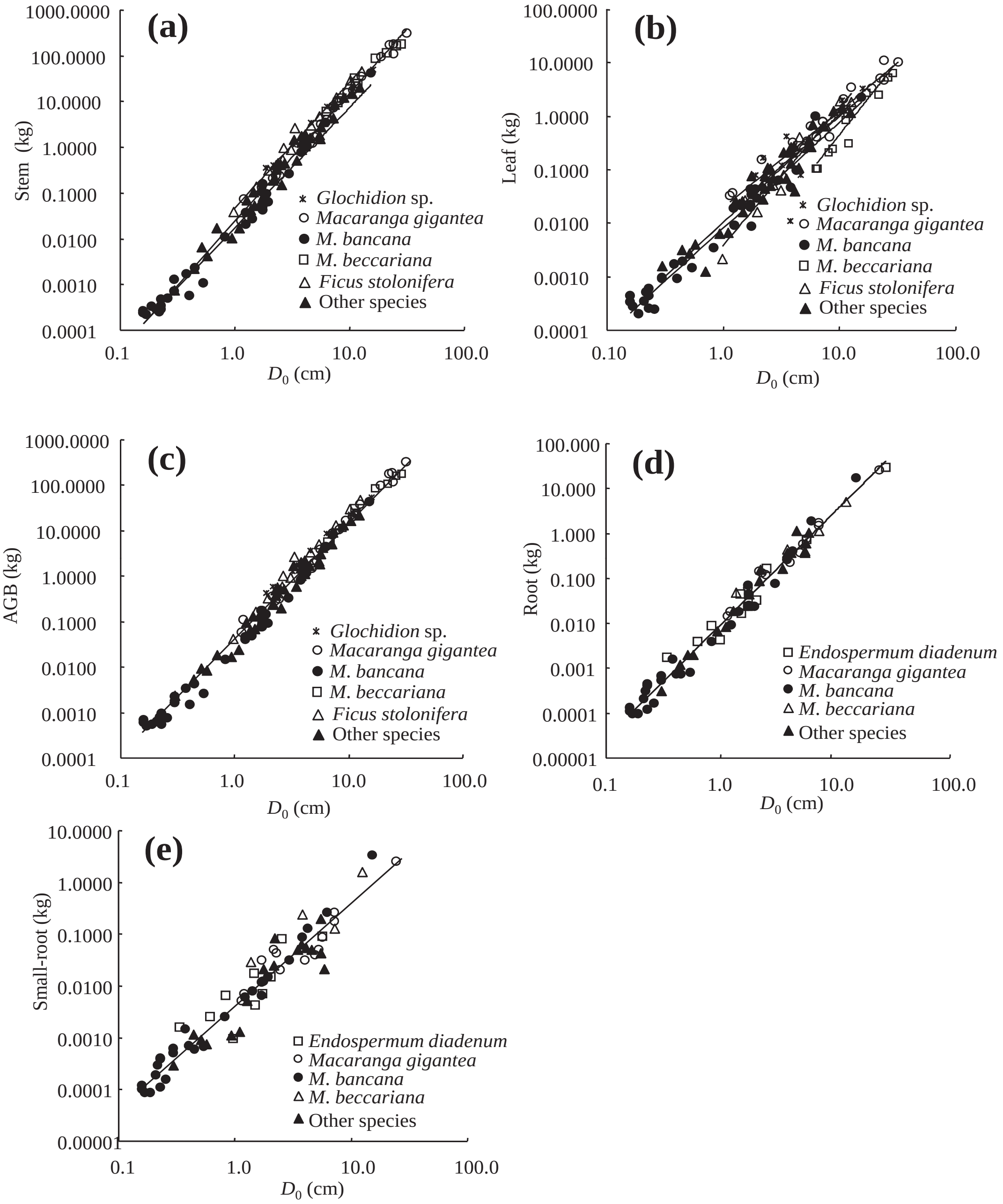

Fig. 2 Allometric relationships between above-ground parts biomass and D_0 in early successional secondary forest trees. Stem biomass (a), leaf biomass (b), total above-ground biomass (AGF) (c), total root biomass (d) and small-root biomass (e) in relation to $D_{0.}$ The regression coefficients appear in Table 3**.**

biomass with dbh or D_0 may result from the similar wood density among secondary-forest trees. In general, secondary-forest trees show lower wood density with lower variation among species (from approximately 0.2–0.5 g cm^{-3}) compared to late-successional tropical rain-forest trees (from 0.2–0.8 g cm^{-3}) in the tropical rain forests of South-East Asia (Suzuki 1999). In fact, the specific gravity of our studied tree species varied within a small range from 0.29 to 0.53 g cm^{-3}.

Table 3 Results of regression analyses for predicting plant part biomass of subject trees from easily measured stem characteristics ($y = ax^b$) using data from all early successional secondary-forest tree species.

Dependent variable (y)	Independent variable (x)	No. of individuals	a (± SE)	b (± SE)	Adjusted R^2
Total root dry biomass (kg)	dbh(cm)	52	0.0214 ± 0.0022	2.33 ± 0.08	0.94
	D_0 (cm)	77	0.0105 ± 0.0007	2.46 ± 0.05	0.97
	H (m)	73	0.0094 ± 0.0013	2.25 ± 0.10	0.89
Small-root dry biomass (kg)	dbh (cm)	51	0.0078 ± 0.0011	1.80 ± 0.12	0.82
	D_0 (cm)	76	0.0047 ± 0.0004	1.87 ± 0.07	0.92
	H (m)	72	0.0043 ± 0.0006	1.70 ± 0.09	0.83
Leaf dry biomass (kg)	dbh (cm)	107	0.0180 ± 0.0019	1.83 ± 0.07	0.88
	D_0 (cm)	135	0.0094 ± 0.0006	2.01 ± 0.04	0.95
	H (m)	131	0.0083 ± 0.0010	1.86 ± 0.07	0.85
Stem dry biomass (kg)	dbh (cm)	107	0.0602 ± 0.0049	2.55 ± 0.05	0.96
	D_0 (cm)	135	0.0238 ± 0.0012	2.82 ± 0.03	0.99
	H (m)	131	0.0183 ± 0.0020	2.68 ± 0.06	0.94
Above-ground biomass (kg)	dbh (cm)	107	0.0829 ± 0.0063	2.43 ± 0.05	0.96
	D_0 (cm)	135	0.0379 ± 0.0017	2.63 ± 0.03	0.99
	H (m)	131	0.0300 ± 0.0033	2.49 ± 0.06	0.93
Total biomass (kg)	dbh (cm)	51	0.1044 ± 0.0103	2.36 ± 0.08	0.94
	D_0 (cm)	76	0.0493 ± 0.0023	2.52 ± 0.04	0.99
	H (m)	72	0.0444 ± 0.0057	2.27 ± 0.09	0.90

In contrast, allocation of leaf biomass with tree size showed greater fluctuation among species than that of root and stem biomass (Fig. 2). Significant interspecific differences were found among *M. gigantea* and *M. hosei*, *M. hosei* and other species groups, and *M. bancana* and *Glochidion* sp. in the regressions of leaf biomass using both dbh and D_0 (Fig. 2, $P < 0.05$, ANCOVA). The allocation of leaf biomass in a plant body can vary greatly with its ontogeny and environmental conditions such as light, soil nutrients and water, even within the same tree species (Lambers et al. 1998). This plasticity may appear in the interspecific differences in the leaf allometric relationships.

Comparison of allometric equations among tropical rainforests

A comparison of allometric equations of total above-ground biomass for various tropical rainforests in Southeast Asia revealed that the equations developed here differed largely from those of other studies. The equation for logged-over forest was located midway between the equations for primary and early successional secondary forests (Fig. 3). Allometric equations for primary tropical forest provided the highest estimate of biomass yield among the equations, while the

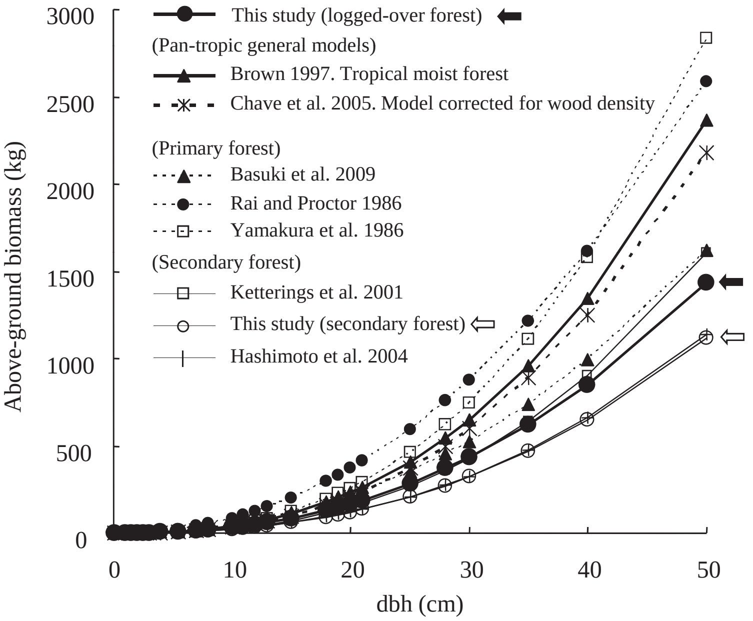

Fig. 3 Comparison with previously reported relationships between above-ground biomass and dbh of tropical moist forest tree. Model parameters and site index are shown in Kenzo et. al. 2009a.

equations for early successional secondary forest provided the lowest estimates. In contrast, the equations for mixed secondary forest dominated by *Havea brasiliensis* and naturally regenerating trees (Ketterings et al. 2001) provided similar values to present equation for logged-over forest. These differences in equations among forest types may be related to the wood density of each forest's trees. Many authors have reported that a higher estimation of the biomass equations for a primary forest was related to higher wood density, while equations of lower wood density for early successional secondary forest trees usually showed a lower biomass estimation (Nelson et al. 1999; Ketterings et al. 2001; Chave et al. 2004; Kenzo et al. 2009b). In fact, the mean wood density of harvested trees in this study (0.497 g cm^{-3}) was an intermediate value between those for the primary (approximately 0.7 g cm^{-3}) and early successional secondary forest trees (approximately 0.3–0.4 g cm^{-3}, Kenzo et al. 2009b). Moreover, the trees used for the estimation of Ketterings' equations (Ketterings et al. 2001), which give a slightly higher estimate than our equations, showed relatively similar wood density (0.6 g cm^{-3}). In addition, the average wood density in our early successional secondary forest species was only 0.354 g cm^{-3}, and this value was lower than the value in most other studies of primary and secondary tropical rain forests. Biomass equations reported by Hashimoto et al. (2004), for trees which also had low wood density (0.32–0.49), were very similar to the biomass equations derived in our study (Fig. 3). Below-ground equations for early successional forest also showed significantly lower biomass estimation than those for primary forest (Niiyama et al. 2010).

Site-specific equations must be considered for accurate estimation of above-ground biomass in both logged-over and early successional tropical forests, although several authors have stated that for tropical forests, local species-specific allometric equations are not needed; instead, generalized allometric relationships must be employed (Chave et al. 2004, 2005). Recent studies in both primary and secondary forests in Southeast Asia reported the importance of site-specific equations for accurate biomass estimation based on application and/or comparison of the proposed pan-tropic general models (e.g. Brown 1997; Chave et al. 2005) and observed biomass data sets for each forest type (Basuki et al. 2009; Kenzo et al. 2009a, 2009b). For example, the general equation derived by Brown (1997) estimated a much higher above-ground biomass, which is an overestimate of approximately 65 % in the case of 40-cm dbh compared with our equation for the present logged-over forest. Even a biomass equation corrected by wood density (Model II.3 for moist forest stands, Chave et al. 2005) overestimated above-ground biomass by approximately 50 % in the case of 40-cm dbh compared with our equation for logged-over forests (wood density in our study is calculated as 0.497 g cm^{-3}). Kenzo et al. (2009b) also reported that correction by wood density (Chave et al. 2005) does not satisfactorily correct the equation for early successional tropical secondary forest trees, which still overestimated the biomass by approximately 20 % in the case of dbh 20 cm. These overestimations suggest that the pan-tropic allometric equations reported by Brown (1997) and even by Chave et al. (2005) have a limited ability to accurately estimate above-ground biomass, and require improvement for application to several kinds of secondary forests, including logged-over tropical rainforests in Southeast Asia.

More data sets for tropical secondary forest trees, such as trees growing in logged-over forest and early successional secondary forest, may be needed in order to improve the general models, especially for correcting equations by wood density (Chave et al. 2005). The lack of data of secondary forest trees in the reported models may cause errors of the model prediction for secondary forest trees, which usually show significantly lower wood density than primary forest trees (Basuki et al. 2009; Kenzo et al. 2009b). In fact, secondary forest trees in Chave’s corrected models account for only 13 % of the total tree data sets and mainly consist of tropical American trees (Chave et al. 2005). Moreover, to improve the models for secondary forest trees such as those in logged-over forests, it is also better to separate the secondary forest trees from the trees in the general model, which mainly consist of primary-forest trees. In fact, Chave et al. (2005) reported that if the model included a different forest type, such as mangrove forest, as a predictive variable, the developed general equations showed a poor fit with the data and poor estimation of above-ground biomass for over 50 % of their study sites.

Conclusions

In this study, we accurately developed allometric relationships for total above-ground biomass as a function of both dbh and tree height in both logged-over and early successional tropical forests that include many tree species. Comparison of above-ground biomass equations for various tropical rainforests and for general models revealed that our allometric equations largely differed from the equations for primary and the pan-tropic general models. Therefore, when choosing the biomass estimation models for above-ground biomass in logged-over and early successional secondary forests of Southeast Asia, it is important to carefully consider their suitability.

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References

Basuki TM, van Laake PE, Skidmore AK, Hussin YA (2009) Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forest. For Ecol Manage 257:1684–1694

Brown S (1997) Estimating biomass and biomass change in tropical forests. A primer. Food and Agriculture Organization of the United Nations, Rome

Chave J, Condit R, Aguilar S, Hernandez A, Lao S, Perez R (2004) Error propagation and scaling for tropical forest biomass estimates. Phil Trans R Soc Lond B 359:409–420

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Fölster FH, Fromard F, Higuchi N, Lescure J-P, Nelson BW, Ogawa H, Puig H, Riera B, Yamakura T (2005) Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia 145:87–99

Hashimoto T, Tange T, Masumori M, Yagi H, Sasaki S, Kojima K (2004) Allometric equations for pioneer tree species and estimation of the aboveground biomass of a tropical secondary forest in East Kalimantan. Tropics 14:123–130

Hattori D, Kenzo T, Yamauchi N, Irino KO, Kendawang JJ, Ninomiya I, Sakurai K (2013) Effects of environmental factors on growth and mortality of *Parashorea macrophylla* (Dipterocarpaceae) planted on slopes and valleys in a degraded tropical secondary forest in Sarawak, Malaysia. Soil Sci Plant Nutri 59:218–228

Kendawang JJ, Ninomiya I, Kenzo T, Ozawa T, Hattori D, Tanaka S, Sakurai K (2007) Effects of burning strength in shifting cultivation on the early stage of secondary succession in Sarawak, Malaysia. Tropics 16:309–321

Kenzo T, Ichie T, Ozawa T, Kashimura S, Hattori D, Irino KO, Kendawang JJ, Sakurai K, Ninomiya I (2007) Leaf physiological and morphological responses of seven dipterocarp seedlings to degraded forest environments in Sarawak, Malaysia: a case study of forest rehabilitation practice. Tropics 17:1–16

Kenzo T, Furutani R, Hattori D, Kendawang JJ, 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

Kenzo T, Ichie T, Hattori D, Itioka T, Handa C, Ohkubo T, Kendawang JJ, Nakamura M, Sakaguchi M, Takahashi N, Okamoto M, Tanaka-Oda A, Sakurai K, Ninomiya I (2009b) Development of allometric relationships for accurate estimation of above- and below-ground biomass in tropical secondary forests in Sarawak, Malaysia. J Trop Ecol 25:371–386

Kenzo T, Ichie T, Hattori D, Kendawang JJ, Sakurai K, Ninomiya I (2010) Changes in above-and belowground biomass in early successional tropical secondary forests after shifting cultivation in Sarawak, Malaysia. For Ecol Manage 260:875–882

Kenzo T, Furutani R, Hattori D, Tanaka S, Sakurai K, Ninomiya I, Kendawang JJ (2015) Aboveground and belowground biomass in logged-over tropical rain forests under different soil conditions in Borneo. J For Res 20:197–205

Ketterings QM, Coe R, Noordwijk MV, Ambagau Y. Palm CA (2001) Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. For Ecol Manage 146:199–209

Kira T, Shidei T. 1967. Primary production and turnover of organic matter in different forest ecosystems of the western Pacific. Jpn J Ecol 17:70–87

Lambers H, Chapin FS, Pons TL (1998) Plant physiological ecology. Springer-Verlag, New York

Nelson BW, Mesquita R, Pereira JLG, de Souza SGA, Batista T, Couto LB (1999) Allometric regressions for improved estimate of secondary forest biomass in the central Amazon. For Ecol Manage 117:149–167

Niiyama K, Kajimoto T, Matsuura Y, Yamashita T, Matsuo N, Yashiro Y, Ripin A, Kassim AR, Noor N (2010) Estimation of root biomass based on excavation of individual root systems in a primary dipterocarp forest in Pasoh Forest Reserve, Peninsular Malaysia. J Trop Ecol 26:271–284

Rai SN, Proctor J (1986) Ecological studies on four rainforest in Karnataka India. J Ecol 74:439–454

Suzuki E (1999) Diversity in specific gravity and water content of wood among Bornean tropical rainforest trees. Ecol Res 14:211–224

Yamakura T, Hagihara A, Sukardjo S, Ogawa H (1986) Aboveground biomass of tropical rain forest stands in Indonesian Borneo. Vegetatio 68:71–82