BIODIVERSITAS
Volume 20, Number 9, September 2019
Pages: 2427-2436

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d200901

Allometric equations to estimate the above-ground biomass of trees in the tropical secondary forests of different ages

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Manuscript received: 28 June 2019. Revision accepted: 1 August 2019.

Abstract. *Karyati, Ipor IB, Jusoh I, Wasli ME. 2019. Allometric equations to estimate the above-ground biomass of trees in the tropical secondary forests of different ages. Biodiversitas 20: 2427-2436.* The allometric equations for trees of secondary forests of different ages in abandoned lands after shifting cultivation are still rarely available. The objective of this study was to develop allometric equations to estimate the above-ground biomass (AGB) of trees (DBH of $\geq$ 5 cm) in the tropical secondary forest of different ages, namely 5, 10, and 20 years after abandonment. The selected trees in this study represented the dominant and rare species and DBH classes in each study site. The trunk dry biomass and AGB showed strong correlations (adjusted R^2= 0.59-0.95) with diameter at breast height (DBH) and height. The leaf and branch dry biomass had weak correlations with height (adjusted R^2=0.36-0.50). The developed allometric equations were suitable for trees of secondary forests of different ages, because the selected samples used in the destructive method were based on a field inventory data of forest structure and floristic composition.

Keywords: Allometric equation, biomass, destructive method, secondary forest

INTRODUCTION

There are vast areas of swidden fallow secondary forests in the tropics and it is important to measure the regrowth rates of these forests and to estimate their potentials as carbon sinks (Hashimotio et al. 2000). Tree species richness and dominance are important factors to consider in estimating tree carbon storage in hyperdiverse forests (Ruiz-Jaen and Potvin 2010). Like any natural forest ecosystem, secondary forests provide both tangible and intangible goods and services. Secondary forests contribute to the sequestration of carbon, the conservation of biodiversity and the protection of soil, especially in the recovery of soil fertility after cultivation (Perera 2001). The total standing above-ground biomass (AGB) of woody vegetation is often one of the largest carbon pools. The AGB comprises all woody stems, branches, and leaves of living trees, creepers, climbers, epiphytes, and herbaceous undergrowth (Hairiah et al. 2001). The estimation of AGB is an essential aspect of studies of carbon stocks as well as the effects of deforestation and carbon sequestration on the global carbon balance (Ketterings et al. 2001). Brower et al. (1990) stated that because direct measurement of biomass cannot be made on the entire community or population, samples must be taken from a community or population. Ketterings et al. (2001) pointed out that weighing tree biomass in the field is undoubtedly the most accurate method of estimating AGB, but it is extremely time-consuming and destructive, generally limited to small areas and small tree sample sizes.

An estimate of the vegetation biomass can provide information about the nutrients and carbon stored in the vegetation as a whole, or the amount in specific fractions such as extractable wood (Hairiah et al. 2001). Allometry is an effective method for accurately estimating biomass of trees, tree components and stands. The labor and expense of constructing and validating the necessary equations limit the application of the allometric approach in biomass sampling (MacDicken 1997). It is hardly ever possible to measure all biomass on a sufficiently large sample area by destructive methods and some allometric equations are used to estimate the biomass of individual trees based on an easily measured property such as their trunk diameter (Hairiah et al. 2001). Various dimensions and partial biomass of trees, such as component parts of bole wood, bark, branch, and foliage mass are estimated from diameter at breast height (DBH) by allometric correlation method (Basuki et al. 2009; Curtis 2008).

Allometric equation is regression expressing the relationship between the dimension of a tree or different parts of plants with the biomass (Heriansyah et al. 2002; Ministry of Forestry Indonesia 2011). Regression models are used to convert inventory data into an estimate of the biomass of trees (Chave et al. 2005; Ministry of Forestry Indonesia 2011). Once an allometric equation has been established for different classes of trees in a vegetation type, one only needs to measure the DBH or other parameters, such as height, used as a basis for equation to estimate the biomass of individual trees and total biomass or carbon content (Hairiah et al. 2001; Heriansyah et al. 2002). To measure the biomass of vegetation that includes trees is not easy, especially in mixed, uneven-aged stands. It requires considerable labor and it is difficult to obtain an accurate measurement given the variability of tree size distribution (Hairiah et al. 2001).

The allometric equations for trees in swidden fallow secondary forests of different ages, such as 5, 10, and 20 year-fallow periods are still rarely available. Several previous developed allometric equations are mainly for trees of primary rain forests (Basuki et al. 2009; Brown 1997; Chamber et al. 2001; Chave et al. 2005; Kawahara et al. 1981; Rai and Proctor 1986; Yamakura et al. 1986), while several allometric equations for trees of secondary forests were reported by Hashimoto et al. (2004), Kenzo et al. 2009a, Kenzo et al. (2009b), Ketterings et al. (2001), Kiyono and Hastaniah (2005); Nelson et al. (1999) and Sierra et al. (2007). When no specific allometric equations to estimate AGB at different age secondary forests is available, these proposed equations may be used to estimate AGB at different stages of fallow periods. Data on the structure, floristic composition, and diversity of the secondary forests of different ages are needed to estimate their AGB and carbon sequestration. Because it is crucial to accurately estimate AGB in secondary forests of different ages, the suitable allometric equations need to be developed. This study was conducted to develop allometric equations for accurate estimation of AGB at the different stages of fallows.

MATERIALS AND METHODS

Study sites

The study was carried out in 5-, 10-, and 20-year-old secondary forest in Sarawak, East Malaysia, respectively located in 01°04'43.3"N 110°59'02.0"E, 01°03'55.9"N 110°55'51.4"E, and 01°03'59.3"N 110°53'34.4"E. The previous study on composition and diversity of trees (Karyati et al. 2018) as well as their soil properties (Karyati et al. 2014) has been done in these study sites. The forest type in the study plots was lowland mixed dipterocarp forest with heath forest (kerangas) (Kendawang et al. 2007). The soil was dominated by acidic soil (pH (H_2O) < 5) having low content of T-C, T-N and exchangeable bases (Karyati et al. 2014).

Procedures

Selecting sample trees

A total number of 30 trees (DBH of $\geq$ 5 cm) were selected in each age class (5, 10, and 20 years old) of secondary forests, with consideration of the species and DBH, not considering individuals with damaged crowns or broken trunks. Almost 90% of the selected trees were categorized as the dominant species in terms of density and Importance Value Index (IVi) in each study site as reported by Karyati et al. (2018), while few selected trees represented the rare species. The DBH of selected trees proportionally represented each DBH class in each study site.

Biomass measurements

The standing DBH (1.3 m) of selected trees were measured using diameter tapes. Measurement of the total height of the sample trees was completed once the trees had been felled. The harvested trees were divided into several factions, each of which was 1 meter-long. After that, parts of the trees were separated into leaves and twigs (hereafter called leaves), branches, and trunks in the field. All fractions were weighed at the field in fresh condition. The scale used depended on the estimated weight of the fraction to be weighed. Three or four disk samples of trunk of 2-5 cm thick were taken by cutting a cross-section of the trunk with a minimum size of a quarter of the trunk circumference. Three disk samples were collected from the harvested trees with less than 10 fractions and 4 disk samples were collected for the harvested trees with $\geq$ 10 fractions. Five branch samples were taken by cutting a cross-section of the branch, 20-30 cm in length, from each sample tree. Five leaf and twig samples, 100-300 grams in weight, were taken from each sample tree.

Data analyses

The wood density (WD) of each disk sample was determined using the formula below (Bowyer et al. 2003; Chave 2006; Marklund 1986):

$$WD = dw / V \quad (1)$$

Where: WD = wood basic density (g cm^{-3}); dw = oven dry weight (g); V = saturated volume (cm^3).

The total oven-dry weight of each tree part was determined using the following formula (Hairiah et al. 2001; Hairiah and Rahayu 2007; Ministry of Forestry Indonesia 2011):

$$dw = (sdw \times fw) / sfw \quad (2)$$

Where: dw = total dry weight (kg); sdw = dry weight of the sample (g); fw = total fresh weight (kg); sfw = fresh weight of the sample (g).

In the first stage of developing allometric equations for estimating AGB in the study sites, the five selected allometric equations of AGB were tested:

$$y = a + b\,x \quad (3)$$
$$y = ax^b \quad (4)$$
$$y = a + b\,(\ln x) \quad (5)$$
$$(\ln y) = a + b\,x \quad (6)$$
$$(\ln y) = a + b\,(\ln x) \quad (7)$$

Where: y = total dry weight or biomass of each plant part, such as trunk, branches, leaves, and total above ground biomass (TAGB) (kg); x = diameter at breast height (DBH, cm), total height (H, meter), and ($DBH^2 \times H$) (cm^2 m); 'a' and 'b' = coefficients estimated by regression.

All regression analyses were carried out using SPSS version 18 for windows (SPSS Japan, Tokyo, Japan). The R^2 values were determined to evaluate precision among all tested allometric equations. To choose the most appropriate regression, several stages, such as analyses of all tested possible regressions, elimination of the inappropriate regressions, and then selection of the best regression were carried out. The best regression was selected based on the goodness of fit with focusing on the suitable scatter plot, good P values and the high values of adjusted R^2 among all tested regressions.

RESULTS AND DISCUSSION

The height and diameter of selected sample trees

The DBH and height classes of selected sample trees for estimation of AGB are shown in Figure 1. The DBH range was 5.0-17.4 cm and height was 5.0-12.5 m for selected sample trees in the 5-year-old secondary forest (Table 1). In 10-year-old secondary forest, the destructive sample trees varied from 5.9 to 32.9 cm in DBH and 6.0 to 21.0 m in height as shown in Table 2. The harvested trees ranged from 5.7 to 41.0 cm in DBH and from 7.0 to 22.5 m in height in the 20-year-old secondary forest as described in Table 3.

The DBH of sampled trees had a positive correlation with their total height (Figure 2). The equations of these relationships were "H=0.43 (DBH)+4.95" (n=30; R^2=0.55), "H=0.32 (DBH)+7.84" (n=30; R^2=0.58), and "H=0.40 (DBH)+8.6" (n=30; R^2=0. 66) in the 5-, 10-, and 20- year-old secondary forests, respectively. The 'H' is total height (m) and 'DBH' is diameter at breast height (cm).

Above-ground biomass of trees

Tables 1, 2, and 3 summarize the DBH, total height (H), dry weight (kg) of tree part biomass, and TAGB in the 5-, 10-, and 20-year old secondary forests. In the 5- year-old secondary forest, the 30 selected trees belonged to 21 genera and 14 families. The dry weight varied from 0.30 to 7.05 kg for leaves, 0.80 to 22.24 kg for branches, 1.50 to 49.12 kg for trunk, and 2.04 to 68.78 kg for TAGB in 5-year-old secondary forest. *Artocarpus elasticus* Reinw. with 5.1 cm DBH and 6.9 m height was the only sample without branch. This species had the lowest dry weight of trunk (1.50 kg) and TAGB (2.04 kg) among all selected species. Generally, the high value of DBH and total height were correlated with the high dry weight of leaf, branch, trunk, and TAGB for sample trees in this study site as mentioned in Table 1.

The 30 selected species belonged to 19 genera and 12 families in the 10-year-old secondary forest. The dry weight of trees varied from 0.50-39.68 kg, 1.06-87.96 kg, 2.73-280.81 kg, and 4.29-408.44 kg for leaves, branches, trunk, and TAGB, respectively. Several species of the genera *Alstonia*, *Cratoxylum*, *Macaranga*, and *Litsea* showed variation in terms of dry weight of plant parts. The results showed that the largest and tallest sample tree reached the highest dry weight of all plant parts, and vice versa. Most of the selected trees with higher values of DBH and total height also had higher values of dry weight of tree parts in the 10-year-old secondary forest as presented in Table 2.

The 30 selected trees in the 20-year-old secondary forest were included in 26 genera and 21 families. The dry weight of leaves, branches, trunk, and TAGB varied from 0.16 to 34.48 kg, 2.15 to 163.54 kg, 4.38 to 525.90 kg, and 7.97-683.91 kg, respectively (Table 3). The variation of dry weight in different plant parts was shown by *Cratoxylum* spp. and *Artocarpus* spp. The largest selected tree reached the highest dry weight of tree part biomass, while the smallest one had the lowest dry weight in the 20-year-old secondary forest. The higher values of dry weight of all tree parts were shown by the selected trees which had the larger DBH and total height.

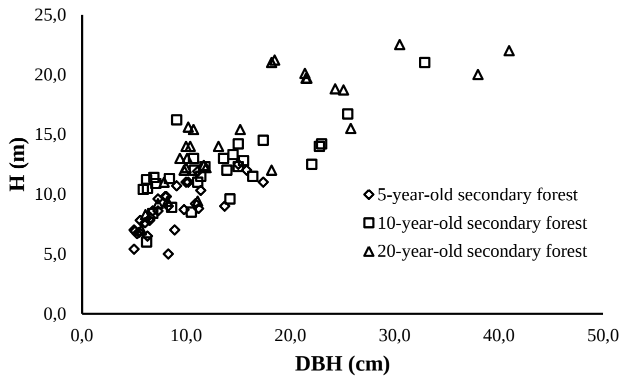

Figure 2. The DBH and total height of sampled trees to develop alometric equations. ◇ 5-year-old secondary forest : "H=0.43 (DBH) + 4.95" (n=30, R^2=0.55); □ 10-year-old secondary forest : "H=0.32 (DBH) + 7.84" (n=30, R^2=0.58); Δ 20-year-old secondary forest : "H=0.40 (DBH) + 8.6" (n=30, R^2=0.66)

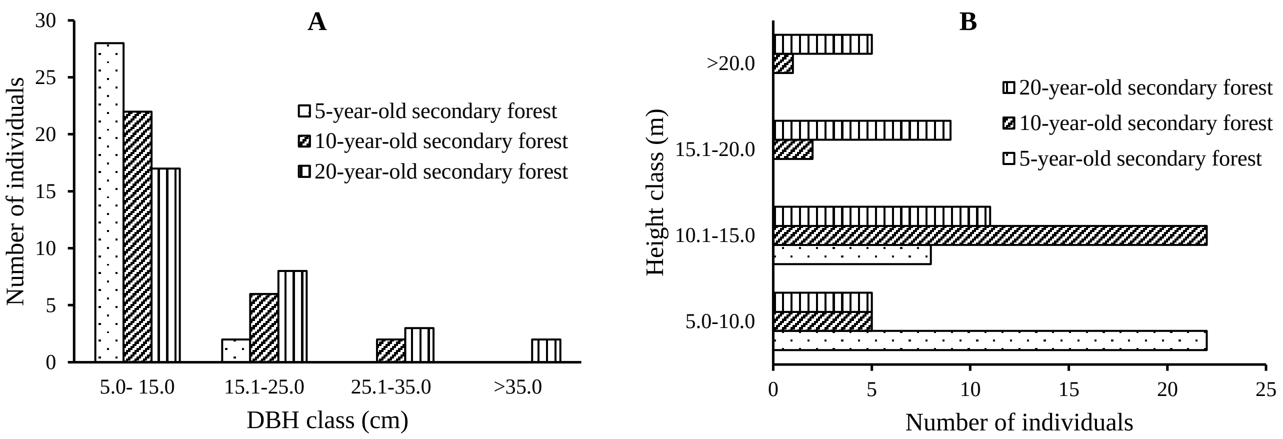

Figure 1. The distributions of (A) DBH classes and (B) height classes of sample trees to develop allometric equations.

Wood density

The relationship between DBH and WD of the selected sample trees was illustrated in Figure 3. The equations of these relationship were "WD=-0.01 (DBH)+0.52" (n=30; R^2=0.10), "WD=0.01 (DBH)+0.33" (n=30; R^2=0.09), and "WD=-0.01 (DBH)+0.52" (n=30; R^2=0.11) in the 5, 10, and 20-year-old secondary forests, respectively. This indicated that WD did not relate to DBH. The results showed that increasing DBH was not followed by an increase in WD density. This trend was similar to the result of previous studies by Baker et al. (2004), Basuki et al. (2009), and Nogueira et al. (2005, 2007).

The average WD of harvested trees in this study was 0.42 g cm^{-3}, 0.39 g cm^{-3}, and 0.45 g cm^{-3} for the 5- 10- and 20 year-old secondary forests as shown in Tables 1, 2, and 3. These values were lower than those reported by Kenzo et al. (2009a), Kiyono and Hastaniah (2005), and Nelson et al. (1999). The mixed species of logged-over tropical rain forest in Sabal and Balai Ringin, Sarawak, Malaysia had average WD of 0.497 g cm^{-3} (Kenzo et al., 2009a), while the average WD of trees in secondary forest with mainly *Schima wallichii* in Kalimantan, Indonesia was 0.67 g cm^{-3} (Kiyono and Hastaniah 2005), and the average WD of mixed species of secondary forest in Central Amazon was 0.54 g cm^{-3} (Nelson et al. 1999).

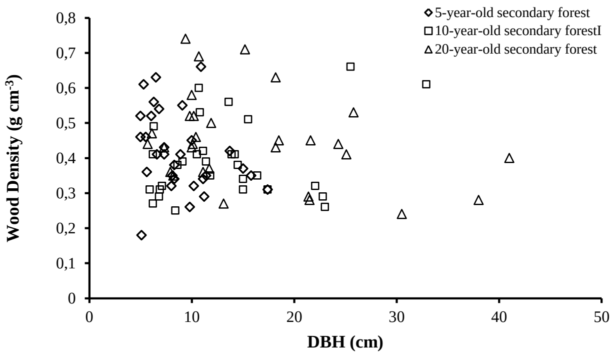

Figure 3. Relationship between DBH and wood density of selected sample trees to assessed allometric equations. ◇ 5-year-old secondary forest, WD=-0.01 (DBH) + 0.52 (n=30; R^2=0.10); □ 10-year-old secondary forest, WD=0.01 (DBH) + 0.33 (n=30; R^2=0.09); △ 20-year-old secondary forest, WD=-0.01 (DBH) + 0.52 (n=30; R^2=0.11)

Table 1. All data sets for diameter at breast height (DBH), total height (H), dry weight (kg) of tree part biomass, total above-ground biomass (TAGB) and wood density (WD, g cm^{-3}) in the 5-year-old secondary forest

Tree Code	Family	Species	DBH (cm)	H (m)	Leaves (kg)	Branches (kg)	Trunk (kg)	TAGB (kg)	WD (g cm^{-3})
T1	Euphorbiaceae	*Macaranga gigantea* Mull. Arg.	11.2	8.8	4.22	13.68	14.11	32.01	0.29
T2	Rubiaceae	*Nauclea subdita* Merr.	8.0	9.8	1.16	2.69	8.31	12.16	0.32
T3	Euphorbiaceae	*Endospermum diadenum* (Miq.) Airy Shaw	11.1	11.9	2.50	4.39	20.09	26.98	0.34
T4	Clusiaceae	*Cratoxylum arborescens* Blume.	11.4	10.3	5.47	8.05	18.61	32.14	0.35
T5	Dilleniaceae	*Dillenia suffruticosa* Martelli	8.3	5.0	0.91	2.91	4.03	7.85	0.38
T6	Euphorbiaceae	*Macaranga trichocarpa* Mull. Arg.	8.1	9.8	1.71	3.27	7.71	12.69	0.35
T7	Rhamnaceae	*Alphitonia excelsa* Reissek ex Endl.	10.0	11.0	2.18	4.70	16.54	23.42	0.45
T8	Myrtaceae	*Syzygium polyanthum* Walp.	10.9	9.2	6.65	22.24	22.80	51.68	0.66
T9	Verbenaceae	*Callicarpa longifolia* Lam.	8.3	9.0	0.79	6.34	19.41	26.55	0.34
T10	Verbenaceae	*Vitex pubescens* Vahl.	9.1	10.7	2.01	7.77	20.43	30.20	0.55
T11	Euphorbiaceae	*Glochidion arborescens* Blume.	7.3	9.6	2.51	3.04	8.67	14.21	0.43
T12	Rubiaceae	*Timonius flavescens* Baker	6.1	7.6	2.23	4.33	8.84	15.40	0.52
T13	Apocynaceae	*Alstonia scholaris* (L.) R. Br.	9.8	8.7	1.53	1.67	8.03	11.22	0.26
T14	Moraceae	*Ficus aurata* Miq.	5.0	5.4	0.44	2.46	3.85	6.75	0.52
T15	Euphorbiaceae	*Macaranga triloba* Mull. Arg.	10.2	11.0	3.07	3.82	15.94	22.84	0.32
T16	Theaceae	*Adinandra dumosa* Jack	13.7	9.0	7.05	4.36	18.62	30.03	0.42
T17	Euphorbiaceae	*Mallotus macrostachyus* Mull. Arg.	6.6	8.0	0.57	2.22	6.45	9.24	0.41
T18	Moraceae	*Artocarpus elasticus* Reinw.	5.1	6.9	0.54	-	1.50	2.04	0.18
T19	Theaceae	*Ploiarium alternifolium* Melchior.	6.5	7.8	0.32	2.32	5.99	8.63	0.63
T20	Loganiaceae	*Fagraea resinosa* Leenh.	6.8	8.6	0.88	6.05	7.90	14.82	0.54
T21	Euphorbiaceae	*Macaranga hypoleuca* Mull. Arg.	17.4	11.0	5.92	14.81	31.34	52.06	0.31
T22	Aquifoliaceae	*Ilex cymosa* Blume	5.0	7.0	0.87	0.80	3.35	5.02	0.46
T23	Moraceae	*Ficus condensa* King.	5.5	6.8	0.39	2.27	3.42	6.08	0.46
T24	Euphorbiaceae	*Macaranga beccariana* Merr.	5.6	7.8	0.41	0.96	2.73	4.10	0.36
T25	Clusiaceae	*Cratoxylum formosum* Benth. & Hook. f. ex Dyer	5.3	6.7	0.30	1.41	4.96	6.66	0.61
T26	Clusiaceae	*Cratoxylum glaucum* Korth.	6.3	6.5	1.14	1.72	4.04	6.90	0.56
T27	Asteraceae	*Vernonia arborea* Buch. Ham.	7.3	8.6	2.23	2.48	6.96	11.68	0.41
T28	Moraceae	*Artocarpus dadak* Miq.	8.9	7.0	0.59	1.12	3.44	5.14	0.41
T29	Apocynaceae	*Alstonia scholaris* (L.) R. Br.	15.8	12.0	2.09	13.37	39.95	55.41	0.35
T30	Rubiaceae	*Euodia glabra* (Bl.) Bl.	15.0	12.5	4.12	15.54	49.12	68.78	0.37
Total			265.5	264.0	64.78	160.78	387.13	612.69	12.56
Average			8.9	8.8	2.16	5.54	12.90	20.42	0.42
Minimum			5.0	5.0	0.30	0.80	1.50	2.04	0.18
Maximum			17.4	12.5	7.05	22.24	49.12	68.78	0.66

Note: DBH = diameter at breast height; H = height; TAGB = total above ground biomass; WD = wood density.

Table 2. All data sets for diameter at breast height (DBH), total height (H), dry weight (kg) of tree part biomass, total above-ground biomass (TAGB), and wood density (WD, g cm^{-3}) in the 10-year-old secondary forest

Tree code	Family	Species	DBH (cm)	H (m)	Leaves (kg)	Branches (kg)	Trunk (kg)	TAGB (kg)	WD (g cm^{-3})
P1	Clusiaceae	*Cratoxylum arborescens* Blume.	15.0	12.3	9.26	16.31	41.09	66.65	0.34
P2	Theaceae	*Adinandra dumosa* Jack	13.9	12.0	10.74	10.41	42.04	63.19	0.41
P3	Dilleniaceae	*Dillenia suffruticosa* Martelli	8.6	8.9	0.65	6.36	8.63	15.64	0.38
P4	Apocynaceae	*Alstonia pneumatophora* Backer ex Den Berger	13.6	13.0	5.87	16.22	65.84	87.93	0.56
P5	Euphorbiaceae	*Macaranga triloba* Mull. Arg.	14.5	13.3	2.42	11.65	44.84	58.91	0.38
P6	Moraceae	*Ficus aurata* Miq.	10.5	8.5	1.78	10.77	12.66	25.22	0.41
P7	Asteraceae	*Vernonia arborea* Buch. Ham.	17.4	14.5	3.09	9.74	58.57	71.39	0.31
P8	Euphorbiaceae	*Macaranga hypoleuca* Mull. Arg.	11.4	11.5	1.88	6.35	22.39	30.61	0.39
P9	Verbenaceae	*Clerodendron* sp.	10.7	13.0	4.33	8.96	30.58	43.86	0.60
P10	Euphorbiaceae	*Glochidion arborescens* Blume.	10.8	12.0	1.15	7.31	21.65	30.11	0.53
P11	Euphorbiaceae	*Macaranga gigantea* Mull. Arg.	22.8	14.0	17.29	53.60	75.93	146.82	0.29
P12	Moraceae	*Artocarpus elasticus* Reinw.	23.0	14.2	4.42	17.84	68.39	90.65	0.26
P13	Rutaceae	*Euodia glabra* (Bl.) Bl.	16.4	11.5	1.81	7.42	49.87	59.10	0.35
P14	Clusiaceae	*Cratoxylum formosum* Benth. & Hook. f. ex Dyer	11.1	11.0	1.18	6.85	15.03	23.06	0.42
P15	Euphorbiaceae	*Endospermum diadenum* (Miq.) Airy Shaw	14.2	9.6	1.07	5.59	22.11	28.78	0.41
P16	Dipterocarpaceae	*Shorea macrophylla* (de Vriese) P.S. Ashton	15.0	14.2	2.26	4.77	29.61	36.64	0.31
P17	Euphorbiaceae	*Macaranga pruinosa* Mull. Arg.	22.1	12.5	35.59	41.19	67.66	144.44	0.32
P18	Euphorbiaceae	*Macaranga caladifolia* Becc.	7.1	10.9	0.74	3.21	5.26	9.20	0.32
P19	Asteraceae	*Ilex cymosa* Blume	11.8	12.3	2.50	3.46	18.65	24.61	0.35
P20	Euphorbiaceae	*Aporosa* sp.	5.9	10.4	0.55	1.59	4.97	7.11	0.31
P21	Lauraceae	*Litsea crassifolia* Boerl.	6.9	11.4	0.86	1.99	7.72	10.56	0.31
P22	Euphorbiaceae	*Macaranga beccariana* Merr.	8.4	11.3	1.06	2.81	7.57	11.44	0.25
P23	Apocynaceae	*Alstonia spatulata* Blume	32.9	21.0	39.68	87.96	280.81	408.44	0.61
P24	Euphorbiaceae	*Macaranga lowii* King ex Hook. f.	6.8	8.4	0.73	1.65	4.65	7.03	0.29
P25	Euphorbiaceae	*Mallotus macrostachyus* Mull. Arg.	9.1	16.2	0.50	8.08	17.18	25.76	0.39
P26	Lauraceae	*Litsea* sp.	6.2	11.2	0.55	1.92	6.22	8.69	0.41
P27	Verbenaceae	*Vitex pubescens* Vahl.	25.5	16.7	9.30	53.43	208.58	271.31	0.66
P28	Apocynaceae	*Alstonia scholaris* (L.) R. Br.	6.2	6.0	0.50	1.06	2.73	4.29	0.27
P29	Clusiaceae	*Cratoxylum glaucum* Korth.	15.5	12.8	9.36	25.27	55.77	90.40	0.51
P30	Sapindaceae	*Nephelium cuspidatum* Blume	6.3	10.5	1.71	2.89	12.27	16.88	0.49
Total			399.6	365.1	172.84	436.65	1309.22	1918.70	11.84
Average			13.3	12.2	5.76	14.55	43.64	63.96	0.39
Minimum			5.9	6.0	0.50	1.06	2.73	4.29	0.25
Maximum			32.9	21.0	39.68	87.96	280.81	408.44	0.66

Note: DBH = diameter at breast height; H = height; TAGB = total above ground biomass; WD = wood density

The average WD of the sample trees in these study sites was higher than that of *Gmelina arborea* and *Paraserianthes falcataria* in plantation forest i.e. 0.34 and 0.32 g cm^{-3}, respectively (Kawahara et al. 1981) and of mixed species of secondary forest in Niah and Sungai Liku, Sarawak, Malaysia, i.e., 0.35 g cm^{-3} (Kenzo et al. 2009a). The range of values of WD (0.39 to 0.45 g cm^{-3}) resulted in this study was within the range of WD values reported by other studies, such as that of mixed species of moist tropical forest, i.e. 0.40-0.79 g cm^{-3} (Brown 1997), that of mixed species of secondary forest, i.e. 0.29-0.47 g cm^{-3} in East Kalimantan, Indonesia (Hashimoto et al. 2004) and in Sumatra, Indonesia, i.e. and 0.35-0.91 g cm^{-3} (Ketterings et al. 2001).

The allometric equations for trees in the secondary forests

The summary of the selected equations for predicting plant part biomass of subject trees in the study sites is presented in Table 4. The testing of log-linear model (ln y=a+b lnx) and exponential model (y=ax^b) showed the good fitting to related plant parameters (DBH, (DBH^2×H), or H) and plant part biomass. For several tested relationships, the simple linear model (y=a+bx) and semilog model (ln y = a+b x) had good *P* values and high R^2 values, but the scatter plots of these relationships were not the most suitable. The testing of semilog model (y = a+b ln x) showed no goodness of fit for all tested parameters in terms of scatter plot and R^2 values. Generally, the analyses of all tested regression in the 5-, 10-, and 20 years old secondary forests showed many tested allometric equations having relatively high R^2 values.

The log model (ln y = a+b ln x) showed that the dependent variables (leaf, branch, trunk, and AGB) of trees were highly correlated with the independent variables (DBH, (DBH^2×H)) in the 5-,10-, and 20-year-old secondary forests. On the other hand, the exponential model (y=ax^b) was the good equation to relate dependent variables (leaf, branch, trunk, and AGB) of tree and tree height. The weak correlations between branch and all independent variables had relatively low R^2 values in the 5-year-old secondary forest (R^2=0.38-0.53). In addition, height was as a good predictor for trunk dry biomass (in the 5-,10-, and 20-year-old secondary forests) and TAGB (in the 5-and 20-year-old secondary forests).

Table 3. All data sets for diameter at breast height (DBH), total height (H), dry weight (kg) of tree part biomass, total above-ground biomass (TAGB), and wood density (WD, g cm^{-3}) in the 20-year-old secondary forest

Tree code	Family	Species	DBH (cm)	H (m)	Leaves (kg)	Branches (kg)	Trunk (kg)	TAGB (kg)	WD (g cm^{-3})
V1	Euphorbiaceae	*Endospermum diadenum* (Miq.) Airy Shaw	25.1	18.7	12.19	91.03	198.94	302.16	0.41
V2	Theaceae	*Adinandra dumosa* Jack	24.3	18.8	13.07	61.75	226.85	301.67	0.44
V3	Symplocaceae	*Symplocos* sp.	10.1	13.0	1.64	4.84	22.94	29.42	0.44
V4	Euphorbiaceae	*Glochidion arborescens* Blume.	11.9	12.2	6.60	15.79	39.32	61.71	0.50
V5	Rhizophoraceae	*Carallia* sp.	10.4	14.0	1.77	6.24	29.43	37.44	0.46
V6	Rutaceae	*Euodia glabra* (Bl.) Bl.	7.9	11.0	0.33	2.15	10.53	13.01	0.36
V7	Rubiaceae	*Timonius flavescens* Baker	10.7	15.4	0.23	4.47	36.58	41.28	0.69
V8	Dilleniaceae	*Dillenia suffruticosa* Martelli	11.1	9.4	1.24	20.89	11.23	33.36	0.36
V9	Verbenaceae	*Vitex pubescens* Vahl.	6.1	8.3	0.16	2.52	6.56	9.24	0.47
V10	Ulmaceae	*Gironniera nervosa* Planch.	10.0	12.2	6.54	7.39	23.60	37.54	0.43
V11	Moraceae	*Artocarpus integer* (Thunb.) Merr.	5.7	7.0	1.40	2.19	4.38	7.97	0.44
V12	Sapotaceae	*Palaquium decurrens* H.J. Lam	8.2	9.4	1.56	4.05	7.79	13.41	0.35
V13	Fagaceae	*Castanopsis* sp.	7.3	9.2	2.18	3.67	7.42	13.27	0.43
V14	Rubiaceae	*Nauclea subdita* Merr.	15.2	15.4	5.96	13.60	80.78	100.34	0.71
V15	Moraceae	*Artocarpus anisophyllus* Miq.	18.5	21.2	5.05	15.74	123.89	144.68	0.45
V16	Myrtaceae	*Syzygium polyanthum* Walp.	18.2	21.0	10.73	28.09	169.16	207.98	0.63
V17	Dipterocarpaceae	*Hopea* sp.	9.4	13.0	6.18	21.86	39.78	67.81	0.74
V18	Moraceae	*Artocarpus dadak* Miq.	9.8	12.0	1.33	9.60	14.52	25.45	0.52
V19	Lauraceae	*Litsea elliptica* Blume	11.7	12.4	2.95	5.27	22.75	30.98	0.37
V20	Anacardiaceae	*Campnosperma auriculatum* (Blume) Hook. f.	21.5	19.7	6.67	19.59	107.42	133.68	0.28
V21	Sapindaceae	*Nephelium cuspidatum* Blume	10.0	14.0	4.10	5.41	43.43	52.95	0.58
V22	Burseraceae	*Dacryodes rostrata* (Blume) H.J. Lam	10.2	15.6	0.94	5.63	19.75	26.32	0.52
V23	Clusiaceae	*Cratoxylum formosum* Benth. & Hook. f. ex Dyer	25.8	15.5	22.61	68.00	197.68	288.28	0.53
V24	Loganiaceae	*Norrisia malaccensis* Gardn.	18.2	12.0	2.63	19.92	52.96	75.51	0.43
V25	Clusiaceae	*Cratoxylum arborescens* Blume	41.0	22.0	34.48	123.53	525.90	683.91	0.40
V26	Euphorbiaceae	*Aporosa* sp.	30.5	22.5	23.12	112.84	387.73	523.69	0.24
V27	Clusiaceae	*Cratoxylum glaucum* Korth.	38.0	20.0	22.57	163.54	466.48	652.58	0.28
V28	Rhizophoraceae	*Pellacalyx axillaris* Korth.	13.1	14.0	1.39	7.69	43.30	52.37	0.27
V29	Rutaceae	*Timonius borneensis* Valeton	21.4	20.1	7.31	9.78	147.75	164.84	0.29
V30	Apocynaceae	*Alstonia spatulata* Blume	21.6	19.7	8.08	16.28	185.40	209.76	0.45
Total			482.9	448.7	215.02	873.36	3254.23	4342.62	13.47
Average			16.1	15.0	7.17	29.11	108.47	144.75	0.45
Minimum			5.7	7.0	0.16	2.15	4.38	7.97	0.24
Maximum			41.0	22.5	34.48	163.54	525.90	683.91	0.74

Note: DBH = diameter at breast height; H = height; TAGB = total above ground biomass; WD = wood density

The allometric equation of "ln (AGB)=a+b ln (DBH)" to estimate the AGB of different forest types was also reported by Basuki et al. (2009), Brown (1997), Chamber et al. (2001), Hashimoto et al. (2004), Kawahara et al. (1981), Nelson et al. (1999), Rai and Proctor (1986), Sierra et al. (2007) and Yamakura et al. (1986). In contrast, Kenzo et al. (2009a), Kenzo et al. (2009b), and Kiyono and Hastaniah (2005) proposed the model of "ln (AGB)=a× $(DBH)^b$" to estimate AGB. A study on distribution of AGB of *Endospermum diadenum* (Miq.) Airy Shaw (*Terbulan*) and its relationship with DBH and age in Sabal Forest Reserve, Sri Aman showed that foliage branch, stem, and total above ground was highly correlated both with DBH ($r^2 \geq 0.90$) and with age ($r^2 \geq 0.86$) (Bohari, 2007). The developed allometric equations to estimate total AGB as a function of DBH and H showed strong correlation with R^2 of 0.97 to 0.99. There was also a relatively strong correlation for allometric relationship between ($DBH^2 \times H$) and AGB in the logged-over tropical rainforests in Sarawak, Malaysia (Kenzo et al. 2009a).

Comparison among various allometric equations

The estimates of AGB using previously reported relationships for trees with DBH of $\geq$ 5 cm at secondary forests of different ages in the study sites are presented in Table 5. Figure 4 illustrates the comparison with previously reported relationship between AGB and DBH in the study sites. The previous studies of allometric equations for various types of tropical forests were chosen to give comparison on estimated AGB in the study sites. The estimated AGB was 10.17 Mg ha^{-1} in the 5-year-old secondary forest, higher than other estimates using equations by Hashimoto et al. (2004), i.e., 9.80 Mg ha^{-1} and Kenzo et al. (2009b), i.e., 9.79 Mg ha^{-1}. A similar value of AGB (10.50 Mg ha^{-1}) was obtained using equation by Kettering et al. (2001). The value resulted by the developed allometric equation was lower than those using other previous reported equations, i.e., 40.61 Mg ha^{-1} (Rai and Proctor 1986)), 17.52 Mg ha^{-1} (Yamakura et. al. 1986), 17.24 Mg ha^{-1} (Brown 1997), 15.48 Mg ha^{-1} (Nelson et al. 1999), 20.26 Mg ha^{-1} (Chamber et. al. 2001), 14.52 Mg ha^{-1} (Kiyono and Hastaniah 2008), 12.47 Mg ha^{-1} (Sierra et. al. 2007), 22.03 Mg ha^{-1} (Basuki et. al. 2009), and 14.98 Mg ha^{-1} (Kenzo et al. 2009a) (Table 5 and Figure 4.A).

Table 4. The best selected allometric equations for predicting plant part biomass of trees (DBH of ≥ 5 cm) in the study sites

Dependent variable (y)	Independent variable (x)	Equation	*P* value	Adjusted R^2
5-year-old secondary forest				
Leaf dry biomass (kg)	DBH (cm)	$\ln(y) = 2.0576 \times \ln(x) -3.99$	<0.001	0.60
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.8590 \times \ln(x) - 5.12$	<0.001	0.63
	H (m)	$y = 0.08\ (x)^{0.3241}$	<0.001	0.43
Branch dry biomass (kg)	DBH (cm)	$\ln(y) = 1.8312 \times \ln(x) - 2.57$	<0.001	0.53
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.7505 \times \ln(x) - 3.47$	<0.001	0.55
	H (m)	$y = 0.30\ (x)^{0.2845}$	<0.001	0.38
Stem dry biomass (kg)	DBH (cm)	$\ln(y) = 2.0738 \times \ln(x) - 2.18$	<0.001	0.74
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.8759 \times \ln(x) - 3.38$	<0.001	0.81
	H (m)	$y = 0.33\ (x)^{0.3773}$	<0.001	0.72
Above ground biomass (kg)	DBH (cm)	$\ln(y) = 2.0859 \times \ln(x) - 1.75$	<0.001	0.73
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.8703 \times \ln(x) - 2.88$	<0.001	0.78
	H (m)	$y = 0.62\ (x)^{0.3569}$	<0.001	0.62
10-year-old secondary forest				
Leaf dry biomass (kg)	DBH (cm)	$y = 0.29\ (x)^{0.1608}$	<0.001	0.70
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.9466 \times \ln(x) - 6.14$	<0.001	0.69
	H (m)	$y = 0.09\ (x)^{0.2752}$	<0.001	0.36
Branch dry biomass (kg)	DBH (cm)	$\ln(y) = 2.1627 \times \ln(x) - 3.32$	<0.001	0.81
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.9178 \times \ln(x) - 4.77$	<0.001	0.82
	H (m)	$y = 5.0354\ (x) - 46.73$	<0.001	0.50
Stem dry biomass (kg)	DBH (cm)	$\ln(y) = 2.2849 \times \ln(x) - 2.51$	<0.001	0.88
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.9882 \times \ln(x) - 4.18$	<0.001	0.93
	H (m)	$y = 0.47\ (x)^{0.3220}$	<0.001	0.63
Above ground biomass (kg)	DBH (cm)	$\ln(y) = 2.2725 \times \ln(x) - 2.09$	<0.001	0.90
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.9751 \times \ln(x) - 3.70$	<0.001	0.93
	H (m)	$y = 0.80\ (x)^{0.3092}$	<0.001	0.59
20-year-old secondary forest				
Leaf dry biomass (kg)	DBH (cm)	$\ln(y) = 2.0583 \times \ln(x) - 4.17$	<0.001	0.63
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.8075 \times \ln(x) - 5.14$	<0.001	0.62
	H (m)	$y = 0.15\ (x)^{0.2101}$	<0.001	0.46
Branch dry biomass (kg)	DBH (cm)	$y = 1.89\ (x)^{0.1211}$	<0.001	0.80
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.8140 \times \ln(x) - 3.87$	<0.001	0.77
	H (m)	$y = 0.68\ (x)^{0.1991}$	<0.001	0.50
Stem dry biomass (kg)	DBH (cm)	$\ln(y) = 2.4558 \times \ln(x) - 2.59$	<0.001	0.92
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.9898 \times \ln(x) - 3.96$	<0.001	0.95
	H (m)	$y = 0.72\ (x)^{0.2820}$	<0.001	0.85
Above ground biomass (kg)	DBH (cm)	$\ln(y) = 2.3207 \times \ln(x) - 1.89$	<0.001	0.93
	$(DBH^2{\times}H)$ (cm^2m)	$\ln(y) = 0.9277 \times \ln(x) - 3.12$	<0.001	0.95
	H (m)	$y = 1.50\ (x)^{0.2559}$	<0.001	0.80

Note: *P* values of the regression analysis are shown. Adjusted R^2 denotes multiple coefficients of determination

In the 10-year-old secondary forest, the estimated AGB calculated using the selected proposed allometric equations was 28.53 Mg ha^{-1} (Table 5), higher than that using formulas by Hashimoto et al. (2004), i.e.,27.91 Mg ha^{-1} and Kenzo et al. (2009b), i.e., 27.80 Mg ha^{-1}. On the other hand, it was lower than that using the equations of Rai and Proctor (1986), Yamakura et al. (1986), Brown (1997), Nelson et al. (1999), Chambers et al. (2001), Kettering et al. (2001), Kiyono and Hastaniah (2008), Sierra et al. (2007), Basuki et al. (2009), and Kenzo et al. (2009a), which were 104.58, 53.30, 50.72, 43.70, 60.03, 31.58, 42.65, 35.30, 58.01, and 41.25 Mg ha^{-1}, respectively (Figure 4.B).

In the 20-year-old secondary forest, the estimate of AGB was 71.75 Mg ha^{-1} (Table 4), higher than 69.45, 55.58, 69.45, and 54.98 Mg ha^{-1} of AGB calculated using the formulas of Kettering et al. (2001), Hashimoto et al. (2004), Sierra et al. (2007), and Kenzo et. al. (2009b), respectively. However, it was lower than the estimated AGB calculated using the equations from Rai and Proctor (1986), Yamakura et al. (1986), Brown (1997), Nelson et al. (1999), Chambers et al. (2001), Kiyono and Hastaniah (2008), Basuki et al. (2009), and Kenzo et al. (2009a), i.e., 167.77, 119.56, 107.22, 85.45, 128.60, 89.94, 97.98, 76.82 Mg ha^{-1}, respectively (Figure 4.C).

Table 5. Estimation of AGB using various reported relationships for trees (DBH of ≥ 5 cm) in the study sites

Equation	Author	Estimate of AGB (Mg ha^{-1})		
		5-year-old secondary forest	**10-year-old secondary forest**	**20-year-old secondary forest**
ln (AGB)=2.12×ln (DBH)-0.435	Rai and Proctor (1986)	40.61	104.58	167.77
ln (AGB)=2.62×ln (DBH)-2.30	Yamakura et al. (1986)	17.52	53.30	119.56
ln (AGB)=2.53×ln (DBH)-2.13	Brown (1997)	17.24	50.72	107.22
ln (AGB)=2.413×ln (DBH)-1.997	Nelson et al. (1999)	15.48	43.70	85.45
ln (AGB)=2.55×ln (DBH)-2.010	Chambers et al. (2001)	20.26	60.03	128.60
ln (AGB)=2.59×ln (DBH)-2.75	Kettering et al. (2001)	10.50	31.58	69.45
ln (AGB)=2.44×ln (DBH)-2.51	Hashimoto et al. (2004)	9.80	27.91	55.58
ln (AGB)=2.422×ln (DBH)-2.232	Sierra et al. (2007)	12.47	35.30	69.45
$AGB=0.1008×DBH^{2.5264}$	Kiyono and Hastaniah (2008)	14.52	42.65	89.94
ln (AGB)=2.196×ln (DBH)-1.201	Basuki et al. (2009)	22.03	58.01	97.98
$AGB=0.1525×DBH^{2.34}$	Kenzo et al. (2009a)	14.98	41.25	76.82
$AGB=0.0829×DBH^{2.43}$	Kenzo et al. (2009b)	9.79	27.80	54.98
	This study for :			
ln (AGB)=2.0859×ln (DBH)-1.75	5-year-old secondary forest	10.17		
ln (AGB)=2.2725×ln (DBH)-2.09	10-year-old secondary forest		28.53	
ln (AGB)=2.3207×ln (DBH)-1.89	20-year-old secondary forest			71.75

Note: AGB = above ground biomass ; DBH = diameter at breast height

Hashimoto et al. (2004), Kenzo et al. (2009b), and Kettering et al. (2001) equations gave similar values of AGB of trees, particularly for the 5- and 10-year-old secondary forests. Hashimoto et al. (2004) developed the equation from the same forest type of secondary forest in East Kalimantan, Indonesia. The low estimated AGB was probably due to the low wood density (0.29 to 0.47). As mentioned earlier, the wood density of the selected trees varied from 0.18 to 0.66 in the 5-year-old secondary forest, 0.25 to 0.66 in the 10-year-old secondary forest, and 0.24 to 0.74 in the 20-year-old secondary forest, respectively (Tables 1, 2 and 3). Kenzo et al. (2009b) reported that the allometric equation for mixed species of early succession secondary forest in Niah and Sungai Liku, Sarawak, Malaysia used wood density of 0.35. The application of Kettering et al. (2001) formula to estimate the AGB obtained a similar value for the 5-year-old secondary forest, lower value for the 10-year-old secondary forest, and higher value for the 20-year-old secondary forest. Ketterings et al. (2001) used the wood densities of 0.35 to 0.91for the allometric equation for mixed secondary forest with mixed species (0.35 to 0.91 in wood density) in Sumatra, Indonesia.

The estimates of AGB in the 5-, 10-, and 20-year-old secondary forests showed overestimation when using the formulas of Basuki et al. (2009), Chambers et al. (2001), Rai and Proctor (1986), and Yamakura, et al. (1986). These four formulas resulted from studies at primary rain forest in Berau Regency of East Kalimantan (Indonesia), Central Amazon, India (Karnataka), and Sebulu of East Kalimantan (Indonesia), respectively. Different characteristics were shown by the primary and secondary forest, in structure, floristic composition, diversity, age distribution, and disturbance intensity. The reported equations for large-size trees of primary forest or secondary forest with long fallow resulted in higher estimates of AGB, when they were applied to the trees of early-successional-stage secondary forest. Likewise, the application of Nelson et al. (1999) and Sierra et al. (2007) equations in the study sites also resulted in overestimates of AGB. These two formulas were reported for mixed species of secondary forest in Central Amazon and Colombia.

The result using equations of mixed species in moist tropical forest (Brown 1997) and secondary forest with mainly *Schima wallichii* in East Kalimantan, Indonesia (Kiyono and Hastaniah 2005) to calculate AGB showed higher value. This might be due to the higher wood density values of trees in those equations (0.54 for Nelson et al.'s equation; 0.40-0.79 for Brown's equation, 0.67 for Kiyono and Hastaniah's equation) than in the selected species in the study sites. The equations of Kenzo et al. (2009a) for mixed species of logged-over tropical rain forest in Sabal and Balai Ringin, Sarawak, Malaysia, resulted in overestimate of AGB when they were used in the study sites. Although, the study sites of Kenzo et al. (2009a) were adjacent to ours, and similar selected species were used to develop allometric equation, but the forest age and land history were different.

The developed allometric equations resulted in intermediate value of AGB among the results of allometric equations for primary forest (Basuki et al. 2009; Yamakura et al. 1986), the secondary forest composed mainly by *Schima wallichii* (Kiyono and Hastaniah 2008), the logged-over secondary forest (Kenzo et al. 2009a), and the early successional-stage secondary forest (Kenzo et al. 2009b). The higher estimates were obtained using allometric equation for primary tropical forest (Chambers et al. 2001; Rai and Proctor 1986) and secondary forest (Brown 1997; Nelson et al. 1999). Using the equations for mixed secondary forest dominated by *Hevea brasiliensis* and naturally regenerating trees (Ketterings et al. 2001) and mixed-species (Hashimoto et al. 2004; Sierra et al. 2007) resulted in similar values of TAGB with the developed equation.

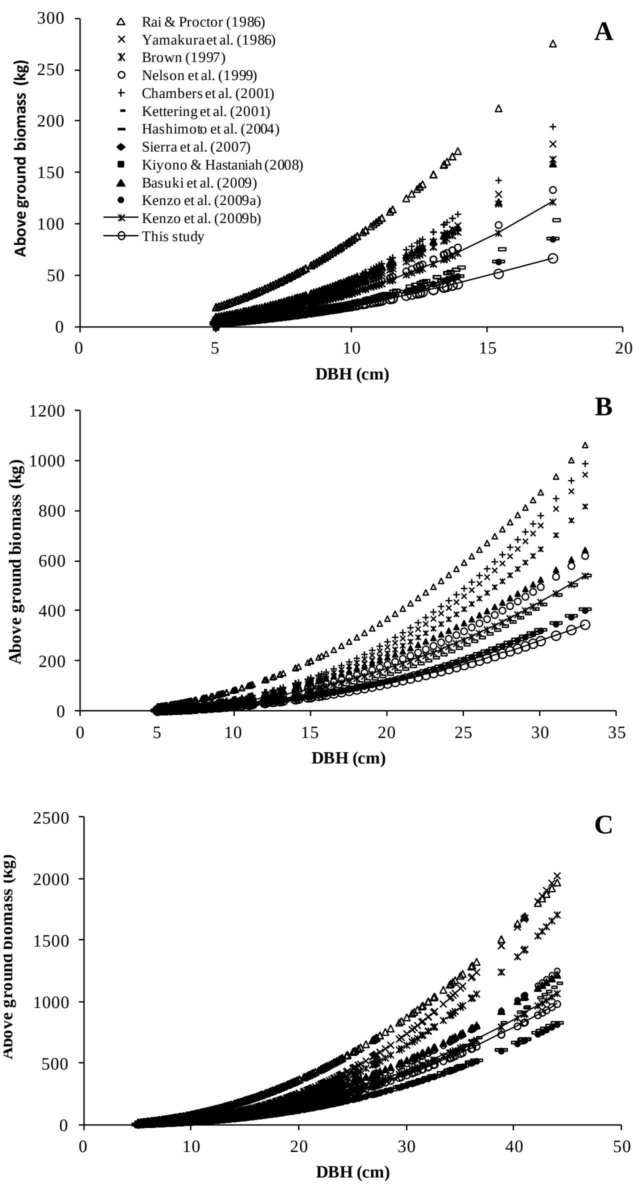

Figure 4. Comparison among various allometric relationships between above ground biomass (AGB) and diameter at breast height (DBH) in the study sites. A. 5-year-old secondary forest, B. 10-year-old secondary forest, C. 20-year-old secondary forest

In conclusion, a specific allometric equation must be developed to estimate the AGB of a specific forest, because the use of inappropriate allometric equations will result in inaccurate estimates of AGB.

ACKNOWLEDGEMENTS

We express our acknowledgment and appreciation to Hidir Marzuki, Sekudan Tedong, Salim Arip, and Muhd Najib Fardos for their kind assistance during the field survey.

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