Estimation of above and belowground biomass for grass, herb, and fern species in Peninsula Malaysia

Authors: TANAKA KENZO[1*], REIJI YONEDA[2], MOHAMAD ALIAS AZANI [3]

Address:

[1] *Japan International Research Center for Agricultural Sciences, Tsukuba, Ibaraki, Japan, 305-8686*

[2] *Shikoku Research Center, Forestry and Forest Products Research Institute, Kochi, 780-8077, Japan*

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[3] *Faculty of Forestry, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia*

Corresponding author: *Tanaka Kenzo. Japan International Research Center for Agricultural Sciences, Tsukuba, Ibaraki, Japan, 305-8686

TEL +81-29-837-6363, FAX +81-29-837-6363, e-mail: mona@affrc.go.jp

Abstract

There are no models for estimating the above- and belowground biomass (AGB and BGB) of herbaceous and fern species in Southeast Asia, and therefore we developed a set of allometric equations for this purpose that were applicable to Malaysia. Grass species, herbs, and ferns of different sizes were harvested and excavated to measure the AGB and BGB. After being harvested and oven-dried, the biomass of plant parts was weighed to develop allometric equations between plant size parameters (height and diameter) and biomass. When comparing the allometric equations among the three plant groups (grass, herbs, and ferns), no differences were found between grass and fern groups in both AGB and BGB, whereas herbs versus grass and/or ferns significantly differed. This suggests that the accuracy of the estimation may improve if plant species were separated into these groups. The allometric equation, which pooled all groups, also showed significant relation with high correlation coefficient, and thus it was possible to make estimations with a certain degree of accuracy, even without grouping. The ratio of BGB to AGB (RSR) increased with plant size for herbs and ferns, whereas the RSR was constant with plant size for grasses. These relationships indicated that the RSR potentially used to estimate BGB from AGB with size parameter in each group, though there was larger variation compared with allometric equations. We concluded that developed allometric equations and the RSR can be used to estimate the AGB and/or BGB without the destructive sampling of grassland species in the region.

Keywords: carbon, grassland, herbaceous plant, production, root biomass, root shoot ratio

Introduction

The estimation of plant biomass in tropical regions is essential for evaluating ecosystem production and carbon storage capacity (Gibbs et al. 2007). Biomass estimation techniques have been developed mainly for forest trees with large biomass. By contrast, few studies have been conducted on grasses and fern species (Yuen et al. 2016). However, even in the tropics, herbs and ferns dominate the plant community in artificially degraded land and during the early stages of succession after a large scale disturbance (Garrity et al. 1996; Corlett 2014). For such ecosystems with grass and fern cover, an accurate estimation of biomass is needed to understand the productivity and carbon stock.

There are several methods for estimating biomass in plant ecosystems (Brown 1997). The most accurate method is harvesting and weighing all vegetation in a plot (Ogawa et al. 1965; Kenzo et al. 2015; Yuen et al. 2016; Syahrinudin et al. 2020). This method is accurate but labor intensive and it is not suitable for estimating belowground biomass (BGB) (Kenzo et al. 2009b, 2020; Waring and Powers, 2017). In addition, this method is destructive and cannot be used for continuous monitoring. By contrast, estimating biomass based on the allometric relationships between biomass and plant size parameters (diameter and height) is nondestructive, and thus measurements are repeatable (Chave et al. 2005). The allometric method has been used in various areas and for different vegetation types, particularly in forest ecosystems (Brown 1997; Chave et al. 2005).

Most areas of the tropical rainforest region in Southeast Asia, such as Indonesia and

Malaysia, were originally covered with forests, and thus the majority of the biomass was stored in trees (Corlett 2014). Therefore, biomass estimation by nondestructive methods has been developed for forest trees, whereas there have been few studies of herbs and ferns in the region (Yuen et al. 2016). In recent decades, the area of degraded land in the region, which is mainly covered by herbaceous plants and ferns, has increased due to anthropogenic activities (Garrity et al. 1996; Corlett 2014). Allometric methods for estimating herb and fern biomass are useful for the nondestructive measurement of biomass in these degraded grasslands and other land types, such as just after large disturbances. Most allometric equations for grass and herbs have been developed for grassland plants in temperate and semi-arid regions (Johnson et al. 1988; Nafus et al. 2009; Sanaei et al. 2019; Mahood et al. 2021; Smith et al. 2021). In recent decades, allometric equations for commercial banana crops (Armecin and Coseco 2012) and tropical grassland species have been developed in high-elevation grassland plants and used for biomass estimation in the Andean highlands, Hawaii, and other tropical regions (Oliveras et al. 2014; Cabrera et al. 2017; Youkhana et al. 2017). However, few such equations have been developed for herbaceous plants in the lowland tropical forest regions of Southeast Asia, such as Malaysia (Yuen *et al.*, 2016). There have also been few studies of allometric equations for ferns, except for woody ferns, in any region of the world (Tiepolo et al. 2002). Furthermore, fewer such equations have been developed for estimating BGB than for aboveground biomass (AGB) due to the difficulty of root excavation (Yuen et al. 2016).

In addition to allometric methods, methods using the root/shoot ratio (RSR) have been used to estimate the BGB (Saatchi et al. 2011; Kenzo et al. 2020; Spawn et al. 2020). If the RSR of grasses and ferns is known, it is relatively easy to determine the BGB from the AGB (Mokany et al. 2006). Furthermore, the RSR is also related to plant allocational strategies, which can be useful for determining the ecological characteristics of tropical grassland plants (Cairns et al. 1997; Poorter et al. 2012; Bardgett et al. 2014).

We developed allometric equations and determine the RSR for grassland plants, such as grass, herbs, and ferns, in the tropical rainforest region of Malaysia. Because allometric equations may differ significantly for plants with different morphological characteristics (Niklas 1994), we compared the allometric equations and RSR of three specific groups of plants based on their ecological and morphological characteristics: grass (Poaceae and Cyperaceae), other herbaceous plants (including small shlubs), and ferns.

Materials and Methods

Study site

Our study was conducted in an abandoned grassland after deforestation in Ayer Hitam Forest Reserve (1248 ha, N 3°00′, E 101°38′) and a degraded pasture at the Universiti Putra Malaysia (N2°59′, E101°43′) located in Selangor, Malaysia. The study site has a tropical rainforest climate without clear dry season and temperature seasonality, and an annual rainfall was approximately 2,700 mm (Kenzo et al. 2021). The monthly rainfall from 30 years average (1990 to 2020) kept more than 100 mm except for severe drought event. Average, maximum and minimum annual temperature, were 26.5°C, 33.0°C, and 23.9°C from 2017 to 2019 in Ayer Hitam Forest Reserve. Annual range of monthly mean temperature was 1.8-°C and showed not distinct seasonal change. The soil type is Ultisol (locally known as the Serdang series) and has sandy loam to clay loam textures (Kenzo et al. 2021).

Plant materials and harvesting

We harvested the aboveground parts of 64 individuals and excavated their root systems in March 2019. Due to little seasonality of climate such as rainfall and temperature, plant growth occurred all year round and thus there was almost all growth stage of herbaceous plant simultaneously in the studied region (Barnes and Chan 1990). Therefore, the effect of the sampling season on the allometry may be considered small. We divided harvested plants into three plant groups (sedges/grass, herbs, and ferns) by growth form (Cabrera et al. 2017). We harvested five species in the grass group, ten species in the herb group, and six species in the fern group (Table 1). To develop robust allometric equation with high accuracy, it is important covering small to largest individual rather than number of harvest individual (Chave et al. 2004). Therefore, we preliminary investigated study site to identify largest individual in each group and those were harvested. Number of harvest individual determined more than 20 individuals in each group following previous studies that conducted for herbaceous and fern in tropical region; 15 individual in banana in Philippine (Armecin and Coseco 2012), 14 to 64 individual in grass species in Andes (Cabrera et al. 2017), 22 individuals in tree fern in Brazil (Tiepolo et al. 2002), and 30 individual in sugarcane and other grass species in Hawaii (Youkhana et al. 2017). Because Cabrera et al (2017) reported that estimation error increased in the case of 14 individuals harvested, we conducted more than 20 individuals in each group. The largest individual was 451 cm in height (banana, *Musa* sp.) and the smallest was 10 cm tall (*Digitaria longiflora*, Table 1). The height (H, cm) and diameter at the ground surface (D_0, cm) of all harvested individuals was measured. For individuals that had clumpy stumps, such as Poaceae and ferns, the perimeter of the clump at the ground surface was measured as D_0 (Johnson et al. 1988). The fresh weight of the aboveground and belowground parts of the plants was measured. After measurement, the plants were oven-dried in a laboratory at 70°C for 3 days to obtain the dry weight.

Allometric model

Three plant size parameters were used for the allometric equation: height (H, cm), diameter at the base (D_0, cm), and $D_0^2 \times H$ (cm^3). The following simple allometric equation was used (Chave et al. 2005): $Y = a \times X^b$, where, Y is plant part biomass (dry weight, g), X is plant size parameter, and *a* and *b* are coefficients. Height and diameter data sets of harvested plants among group were tested normality of distribution pattern after logarithmic transformation using Kolmogorov-Smirnov normality test and Shapiro-Wilk significance probability (Sokal and Rohlf 1995; Kerkhoff and Enquist 2009). The most data set are followed normal distribution by the tests, except for herb (P<0.05, Kolmogorov-Smirnov test), though combined parameter with height and diameter (D_0^2H) of herb group was followed normal distribution. The effect of non-normality of herb size to the developed allometric equation may not be as large, because we have harvested individual to cover large to small size to develop robust allometric equation (Chave et al. 2004, 2005-).

Comparison between other biomass estimation models

Developed allometric equations for above–ground biomass were compared with other equations ~~for plant growth in~~from tropical area to understand robustness and adaptability by using root mean square error (RMSE) and correlation coefficient (Cabrera et al. 2017; Youkhana et al. 2017; Sanaei et al. 2019). The comparison was conducted for five plant groups; banana in Philippine (Armecin and Coseco 2012), nepiergrass, energycane and sugarcane in Hawaii (Youkhana et al. 2017), and secondary forest trees in Malaysia (Kenzo et al. 2009b). The RMSEs using those equations were obtained by substituting the measured size and dry weight of this study into each equation. Since RMSEs can only be compared between the same data sets, comparisons within group (grass, herb and fern) were conducted (Sokal and Rohlf 1995). The comparison of below ground biomass was not conducted due to existence of few comparable formulas for herbaceous plants in tropical region.

Statistical analyses

Differences in the intercepts of allometric equations among plant groups were tested by analysis of covariance (ANCOVA, Sokal and Rohlf 1995). The significance of the equations was tested using a regression analysis. All analyses were conducted using SPSS for Windows software (ver. 23.0; IBM Corp., Armonk, NY, USA).

Results

Traits in allometric equations

Significant positive correlations for all allometric equations were observed between AGB and size parameters (D_0, H, and D_0^2H), although the correlation coefficient varied among plant groups (Fig. 1, Table 2). For the herb group, the correlation coefficient of the AGB equation using H was 0.61, while the correlation coefficients were 0.95 and 0.96 when D_0 and D_0^2H were used as size parameters in the AGB equations, respectively. The AGB equations for the grass and fern groups had higher correlation coefficients and ranged between 0.82 to 0.84 for the grass group and 0.90 to 0.95 for the fern group for all three size parameters, respectively. There were also significant positive correlations similar between BGB and size parameters (D_0, H, D_0^2H) for all three groups (Fig. 2, Table 2). The correlation coefficient for the relationship with H was 0.60 for the herb group, while it was as high as 0.95 when D_0 and D_0^2H were used as parameters. The grass group had a correlation coefficient of 0.83 for H, with variation in 0.72 for D_0^2H and 0.67 for D_0. The correlation coefficient of the fern group was 0.82 for H, although D_0 and D_0^2H was higher than 0.98.

When all groups were pooled, an allometric equation was developed for biomass (AGB and BGB) and all size parameters produced a significant correlation (Table 2). The correlation coefficients for ABG and BGB were higher than 0.93 for D_0 and D_0^2H, although the coefficients for H were only 0.60 for AGB and 0.58 for BGB (Table 2).

There were several significant differences in the intercepts of allometric equations among the three groups (ANCOVA, P<0.05), although there were no significant differences between the grass and fern groups for all AGB equations. Significant differences between the grass and herb groups were detected when the AGB equations used H and/or D_0 as parameters. For the AGB equation using D_0^2H there were significant differences between the herb group and both the grasses and fern groups.

For the BGB equations using H and D_0^2H there were significant differences between the herb group and the other two groups, although there were no differences between the grass and fern groups. There were no statistical differences among the three groups for the BGB equation using D_0.

Comparison among other equation in tropical plants

In the height-based allometry, the RMSE was lowest and smallest error when using the equation developed in this study compared with the other five plant equations (Table 3). Similar results were obtained when D_0 was used for the equation for grass and fern group, though the herb equation showed a slightly larger RMSE compared with the equation developed for sugarcane (Table 3). The difference of the RMSE between ~~developed~~ herb and sugarcane equation was 14%. The values of the correlation coefficients for aboveground biomass in this study varied between 0.83-0.95 using diameter and 0.61-0.93 using height in three plant groups (Table 2). –The correlation coefficients of other ~~research~~equations on tropical plants also varied from 0.73-0.98 in diameter (0.73 in tropical grass, 0.88 in tree fern, 0.96 in banana, 0.96 in energycane, 0.97 in sugarcane, and 0.98 in nepiergrass) and 0.51-0.99 in height (0.51 in tropical grass, 0.91 in energycane, 0.93 in nepiergrass, 0.94 in sugarcane and 0.99 in banana), respectively (Tiepolo et al. 2002; Armecin and Coseco 2012; Olivers et al. 2014; Youkhana et al. 2017).

RSR among plant groups

Although the RSR varied with the size parameter, inter-group differences were also observed. The RSR was almost constant with size for the grass group, while for the fern and herb groups there was a significant increase in RSR with size (Fig. 3, Table 4). When the intercepts of the regression lines were compared between the herb and fern groups, which were significantly correlated with size and RSR, there were significant differences for all of H, D_0, and D_0^2H (Fig. 3).

Discussion

Allometric equations developed with high accuracy can be used to estimate both the AGB and BGB of herbs, grasses, and ferns in tropical rainforest regions in Malaysia. For herb equation, the correlation coefficients (r^2) exceeded 0.9 and P<0.001, which indicate a high prediction accuracy, despite the non-normal distribution of the size. It was thought to be due to the large size range (Chave et al. 2004, 2005). Although the accuracy was higher when the species were divided into plant groups, such as herbs, grasses, and ferns, even the equation when all groups were pooled could be used for biomass estimation due to the high correlation coefficient. Mixed-species allometric equations for grasses and herbs have been developed with high accuracy in other regions, which supports the validity of the equation developed here using a mixture of species (Nafus et al. 2009; Oliveras et al. 2014; Cabrera et al. 2017; Sanaei et al. 2019). Separation into growth forms, such as grasses and herbs, has also been shown to improve the accuracy of biomass estimation of grassland plants (Cabrera et al. 2017). The allometric equation using D_0 as a parameter had a higher prediction accuracy than H alone, except for the BGB equation for the grass group. A similar reduction in prediction accuracy using H rather than diameter has also been reported for allometric equations on tree species (Chave et al. 2005; Kenzo et al. 2009ab, 2020).

The grass and fern groups had similar allometric equations, although their taxonomy was very different. This may have been caused by their morphological similarities, such as the shapes of the aboveground parts and root system that defined the parameters of the allometric equations (Niklas 1994). The productive structure of the aboveground parts of both grasses and fern species are categorized as the grass type, and the belowground parts are also similar in morphology, with both groups having fibrous roots (Monsi and Saeki 2005; Schulze et al. 2005). By contrast, the equation for ferns developed in this study may not be applicable to woody ferns due to their significantly different morphology (e.g., tall stem), although they are more closely taxonomically related to ferns than grass species. An allometric equation for woody ferns is not available in Malaysia and adjacent regions, and it is therefore advisable to use the existing equation for other regions or develop an original equation for use in Malaysia (Tiepolo et al. 2002).

It was found that, in the most case, there were large errors when estimating aboveground biomass by applying the equations derived from plants in other tropical species and/or regions to herbs, grass, and ferns in Malaysia. Several researchers also reported that site- or species-specific allometric equation were often more accurate than general equation for tropical trees (Kenzo et al. 2009ab, 2020; van Breugel et al. 2011; McNicol et al. 2015), and it may be similar for herbaceous species. In the case of trees, differences in wood density among study forests and regions are driven factor in the differences in allometric equations, and thus general equation was usually developed by correction of the equation using specific gravity of the wood (~~Brown 1997;~~ Chave et al. 2005). The specific gravity of stems or roots of herbaceous plants and ferns may also be related to the differences in the equations among other studies. Therefore, it is carefully applied when applying equations to estimate the biomass in other regions to Malaysia and vice versa. On the other hand, the values of correlation coefficient obtained in this study are within the range of values obtained in other studies, and in some cases exceed 0.9, which is good predictive accuracy (Chave et al. 2004, 2005). However, in our study, it is unknown the accuracy when adapt the developed equation to other regions, as there is currently little comparable data of herbaceous and fern plants in tropical region. Similar harvest study should be conducted in other regions to address this limitation in the future.

Although accuracy of biomass estimation was lower than using allometric equation, the RSR calculated in this study possibly be used to determine the BGB from the AGB. However, changes in the RSR with the size of individuals, i.e., height and diameter, resulted in significant differences between the plant groups; thus, careful consideration of the plant species and/or groups used is required when using the RSR to determine BGB (Qi et al. 2019; Kenzo et al. 2020). Although the variation in RSR in the grass group was large, it did not show size dependency, indicating that the BGB could be estimated from the AGB without size parameters. By contrast, there was a size dependency in the herb and fern groups and a size parameter was therefore required to estimate BGB from AGB using the RSR. These two groups also had different BGBs for the same size of plant, with ferns having a consistently larger BGB than herbs. The increase in RSR with plant size indicates that the relative allocation to roots increased with growth for these two plant groups. Although the RSR often decreases with growth in trees, it increases in many herbaceous species, and the results for ferns and herbs obtained in this study are consistent with those of previous studies (Poorter et al. 2012; Qi et al. 2019; Kenzo et al. 2020). The increases in relative investment to roots may be due to the increased nutrient and water demand through the root system and/or the increased role of the storage function in recovering from disturbances by sprouting (Poorter et al. 2012). Resilience to damage of aboveground parts, through disturbances such as fire and grazing, may increase with growth in these groups (Guerrero-Campo et al. 2006; Palacio et al. 2007). Similar increases in root biomass as a storage function for sprouting are usually found in grass and shrub species, particularly growth under higher disturbance habitats, such as tropical savanna (van der Maarel and Titlyanova 1989; Bowen and Pate 1993; Schulze et al. 2005; Yan et al. 2013). Because grasslands in tropical rainforest regions also experience fire disturbance and herbivore grazing (Woods 1989; Ashton 2014; Miettinen et al. 2017), the increase in root biomass may aid rapid recovery from such disturbances (Bowen and Pate 1993).

Conclusion

Allometric equations for estimating the ABG and BGB of grasses and ferns, which had not been previously available in Southeast Asia, were developed with high accuracy in this study. Using the equations, AGB and BGB could be estimated nondestructively. The size dependence of the RSR was clarified and the significant differences in RSR among plant groups indicated that the careful adaptation of the RSR for each plant group may require an estimation of BGB from AGB and plant size. Further studies with a larger number of species and study sites will improve the accuracy of biomass estimation models and the adaptability to other regions for grassland species in Southeast Asia.

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Conflict of interest

The authors declare no competing financial interest.

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Figure Legends

Figure 1. Allometric relationships between aboveground biomass (AGB) and plant size parameters in grasses, herbs, and ferns. The AGB in relation to diameter at the ground surface, D_0 (a), height, H (b), and D^2H (c). The regression coefficients are given in Table 2.

Figure 2. Allometric relationships between belowground biomass (BGB) and plant size parameters in grasses, herbs, and ferns. The BGB in relation to diameter at the ground surface, D_0 (a), height, H (b), and D^2H (c). The regression coefficients are given in Table 2.

Figure 3. Relationships between the root shoot ratio (RSR) and plant size parameters in grasses, herbs, and ferns. The RSR in relation to diameter at the ground surface, D_0 (a), height, H (b), and D^2H (c). The regression coefficients are given in Table 3.

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Table 1. Species, plant groups, height (H, cm), diameter at the ground surface (D_0, cm), aboveground biomass (ABG, g), and belowground biomass (BGB, g) of all harvested plants in the study.

Family	Species	Plant group	H	D_0	AGB	BGB
Cyperaceae	*Scleria sumatrensis*	grass	32.0	0.38	1.1	0.74
Cyperaceae	*Scleria sumatrensis*	grass	40.0	0.39	0.903	0.59
Cyperaceae	*Scleria sumatrensis*	grass	49.0	0.69	2.516	1.79
Cyperaceae	*Scleria sumatrensis*	grass	50.0	0.55	3.22	2.47
Poaceae	*Digitaria longiflora*	grass	10.0	0.69	0.681	0.50
Poaceae	*Digitaria longiflora*	grass	13.0	1.08	2.168	1.83
Poaceae	*Digitaria longiflora*	grass	15.0	0.53	0.72	0.66
Poaceae	*Digitaria longiflora*	grass	24.0	1.34	3.715	1.74
Poaceae	*Digitaria longiflora*	grass	27.0	1.32	2.704	1.35
Poaceae	*Eleusine indica*	grass	23.0	0.33	0.59	0.32
Poaceae	*Eleusine indica*	grass	24.5	0.73	0.783	1.85
Poaceae	*Eleusine indica*	grass	31.1	0.90	1.903	1.27
Poaceae	*Imperata cylindrica*	grass	65.0	0.55	3.38	1.66
Poaceae	*Imperata cylindrica*	grass	78.0	0.60	4.01	4.29
Poaceae	*Imperata cylindrica*	grass	84.0	0.63	4.44	4.62
Poaceae	*Pennisetum purpureum*	grass	81.0	2.78	34.2	25.79
Poaceae	*Pennisetum purpureum*	grass	202.0	2.69	30.4	24.88
Poaceae	*Pennisetum purpureum*	grass	204.0	3.55	47.99	49.18
Poaceae	*Pennisetum purpureum*	grass	220.0	4.38	30.8	37.20
Poaceae	*Pennisetum purpureum*	grass	234.0	6.24	55.5	33.14
Compositae	*Adenostemma lavenia*	herb	64.0	0.70	18.973	3.33
Compositae	*Chromolaena odorata*	herb	12.5	0.10	0.093	0.02
Compositae	*Chromolaena odorata*	herb	17.2	0.13	0.236	0.07
Compositae	*Chromolaena odorata*	herb	23.0	0.15	0.211	0.12
Compositae	*Chromolaena odorata*	herb	39.0	0.31	1.189	0.72
Compositae	*Chromolaena odorata*	herb	93.0	0.47	4.007	2.33
Compositae	*Chromolaena odorata*	herb	101.0	0.64	11.382	5.32
Compositae	*Chromolaena odorata*	herb	103.0	0.52	4.508	6.66
Compositae	*Chromolaena odorata*	herb	157.0	0.69	14.067	15.30
Compositae	*Wollastonia* sp.	herb	25.0	0.33	1.15	0.55
Melastmataceae	*Clidemia hirta*	herb	48.0	0.18	0.74	0.42
Melastmataceae	*Clidemia hirta*	herb	138.0	0.84	42.569	20.10
Melastmataceae	*Clidemia hirta*	herb	170.0	0.88	45.73	25.71
Melastomataceae	*Sonerina* sp.	herb	60.0	0.76	23	12.00
Musaceae	*Musa* sp.	herb	174.0	10.20	582	652.00
Musaceae	*Musa* sp.	herb	177.0	3.90	1120	1333.00
Musaceae	*Musa* sp.	herb	325.0	15.90	4190	5283.00
Musaceae	*Musa* sp.	herb	451.0	17.50	5200	6803.74
Rubiaceae	*Spermacoce articularis*	herb	30.0	0.26	0.724	0.37
Verbenaceae	*Stachytarpheta indica*	herb	14.0	0.12	0.088	0.01
Zingiberaceae	*Etlingera* cf. *littoralis*	herb	136.0	1.90	41.4	34.50
Zingiberaceae	*Etlingera* cf. *littoralis*	herb	356.0	2.60	259.4	158.90
Zingiberaceae	*Etlingera* cf. *littoralis*	herb	362.0	2.65	302.2	100.20
Zingiberaceae	*Etlingera* sp.	herb	81.0	1.40	10.534	3.20
Blechnaceae	*Blechnum finlaysonianum*	fern	31.0	0.18	0.68	0.27
Blechnaceae	*Blechnum finlaysonianum*	fern	107.0	1.02	11.35	3.20
Blechnaceae	*Stenochlaena palustris*	fern	41.0	0.40	3.98	3.45
Blechnaceae	*Stenochlaena palustris*	fern	44.0	0.42	4.25	3.88
Blechnaceae	*Stenochlaena palustris*	fern	50.0	0.49	5.62	5.13
Blechnaceae	*Stenochlaena palustris*	fern	55.0	0.56	5.51	4.85

Table 1. Continued.

Family	Species	Plant group	H	D_0	AGB	BGB
Marattiaceae	*Angiopteris evecta*	fern	137.0	5.02	43.40	77.30
Oleandraceae	*Nephrolepis biserrata*	fern	25.0	0.52	0.5	0.42
Oleandraceae	*Nephrolepis biserrata*	fern	28.0	0.15	0.45	0.29
Oleandraceae	*Nephrolepis biserrata*	fern	30.0	0.70	0.68	0.21
Oleandraceae	*Nephrolepis biserrata*	fern	32.0	0.75	0.75	0.74
Oleandraceae	*Nephrolepis biserrata*	fern	33.0	0.80	0.98	0.89
Oleandraceae	*Nephrolepis biserrata*	fern	36.0	0.39	1.03	0.51
Schizaeaceae	*Lygodium salicifolium*	fern	21.0	0.07	0.09	0.03
Thelypteridaceae	*Macrothelypteris* sp.	fern	63.0	1.83	4.67	8.29
Thelypteridaceae	*Metathelypteris* sp.	fern	12.5	0.40	0.12	0.10
Thelypteridaceae	*Metathelypteris* sp.	fern	19.0	0.53	0.31	0.28
Thelypteridaceae	*Metathelypteris* sp.	fern	24.0	0.46	0.41	0.32
Thelypteridaceae	*Metathelypteris* sp.	fern	24.0	0.52	0.33	0.22
Thelypteridaceae	*Metathelypteris* sp.	fern	30.0	0.81	1.30	0.77

Table 2. Results of the regression analysis ($y = ax^b$) predicting the AGB or BGB (y) of sampled plants from plant size parameters (x) among the three plant groups. D_0, diameter at ground surface (cm); H, plant height (cm).

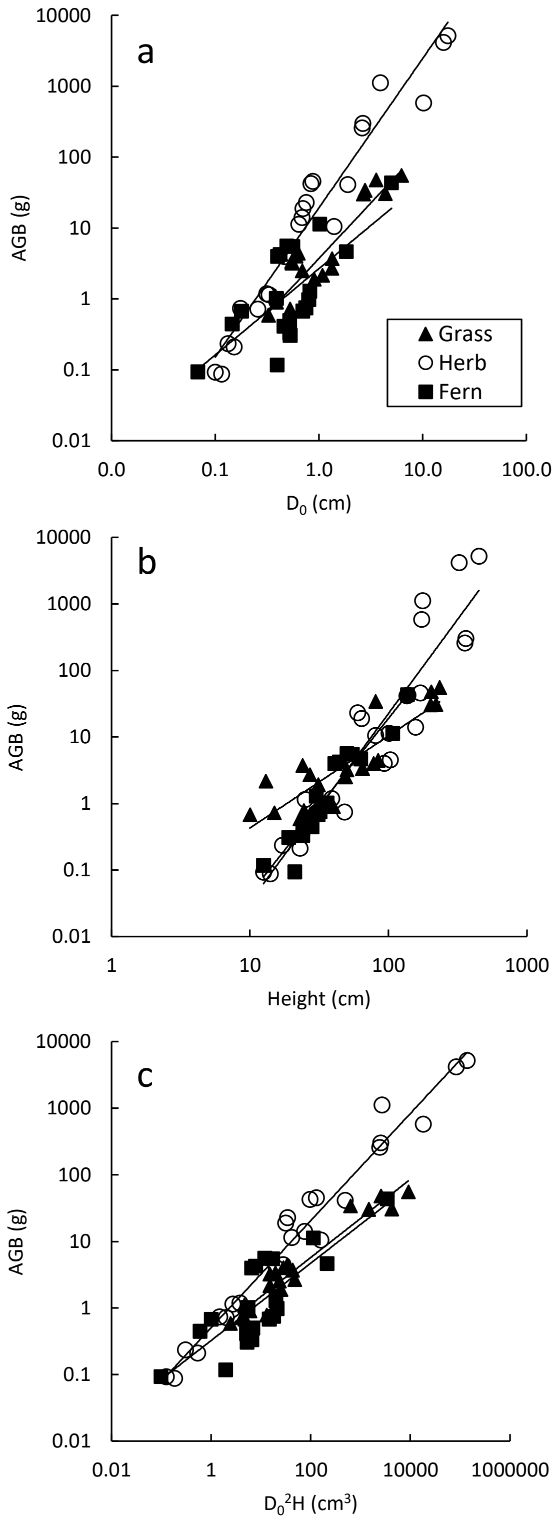
Plant group	Independent variable (x) D_0, H, D_0^2H	AGB				BGB			
		a	*b*	Adjusted R^2	*P*-value	*a*	*b*	Adjusted R^2	*P*-value
Grass	D_0 (cm)	3.730	1.56	0.83	<0.001	2.905	1.6	0.67	<0.001
Herb	D_0 (cm)	19.316	2.11	0.95	<0.001	11.043	2.37	0.96	<0.001
Fern	D_0 (cm)	2.676	1.22	0.90	<0.001	2.348	1.54	0.98	<0.001
All	D_0 (cm)	6.974	1.87	0.93	<0.001	4.903	2.09	0.94	<0.001
Grass	H (cm)	0.0176	1.38	0.82	<0.001	0.011	1.44	0.83	<0.001
Herb	H (cm)	0.0001	2.83	0.61	<0.001	0.00001	3.21	0.60	<0.001
Fern	H (cm)	0.0001	2.64	0.93	<0.001	0.00003	2.85	0.82	<0.001
All	H (cm)	0.0004	2.36	0.60	<0.001	0.0001	2.51	0.58	<0.001
Grass	D_0^2H (cm^3)	0.383	0.59	0.84	<0.001	0.279	0.61	0.72	<0.001
Herb	D_0^2H (cm^3)	0.506	0.80	0.96	<0.001	0.183	0.91	0.97	<0.001
Fern	D_0^2H (cm^3)	0.325	0.58	0.95	<0.001	0.716	0.70	0.99	<0.001
All	D_0^2H (cm^3)	0.321	0.75	0.95	<0.001	0.163	0.82	0.96	<0.001

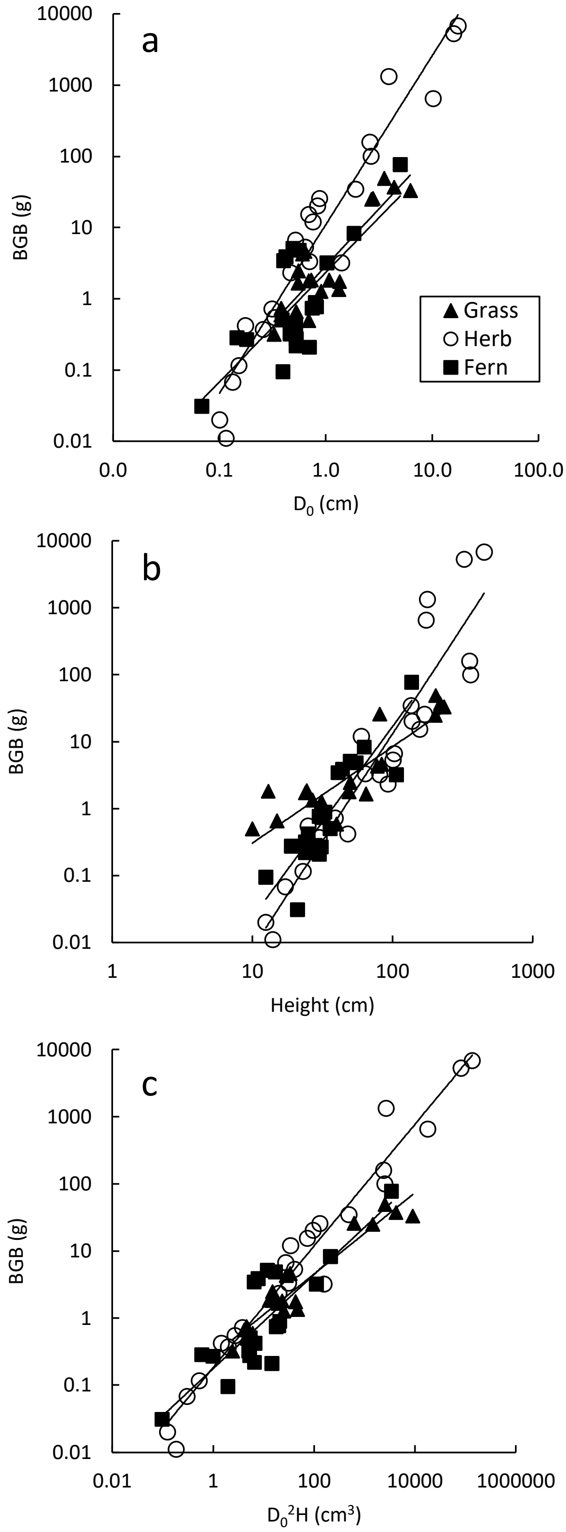
Table 3. Comparison of the root mean square error (RMSE) determined in this study and from other equations in tropical plants. The comparison was conducted for five plant groups: bananas in The Philippines (Armecin and Coseco 2012); napier grass, energy cane, and sugarcane in Hawaii (Youkhana et al. 2017); and secondary forest trees in Malaysia (Kenzo et al. 2009). The numbers in bold indicate the lowest RMSEs among the equations.

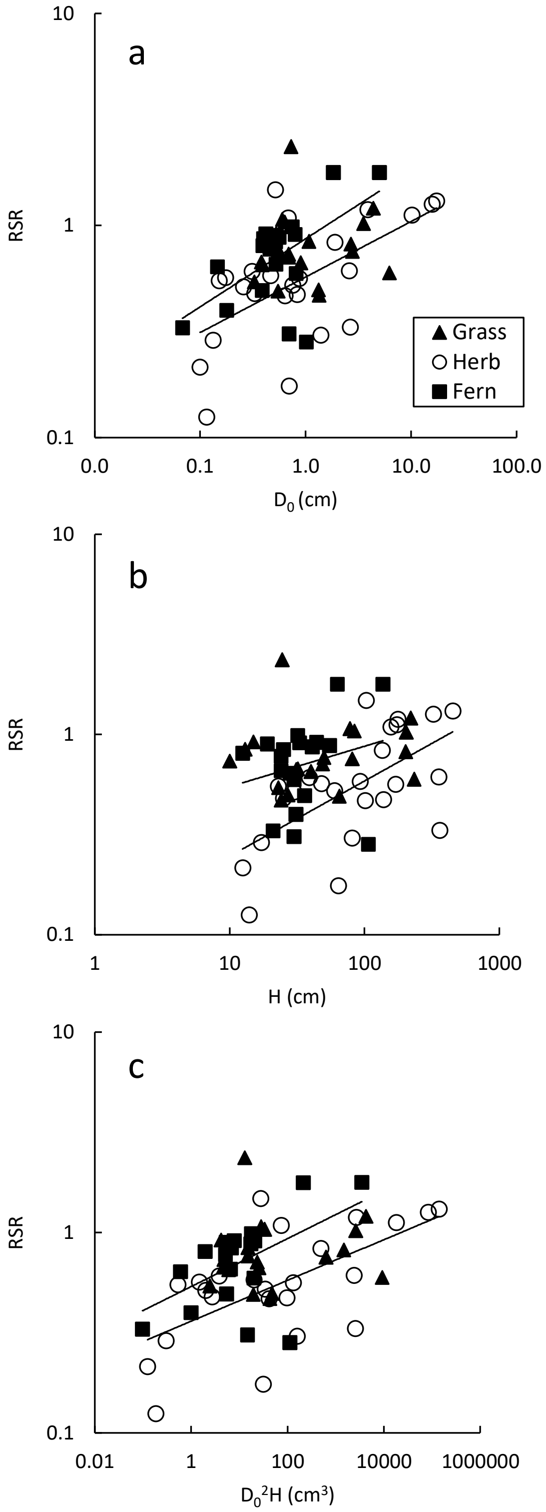
Plant group	Variables	This study	Banana	Nepiergrass	Sugarcane	Energycane	Secondary forest tree
Grass	D_0	**7.2**	20.6	203.0	449.3	929.6	1144.6
Herb	D_0	890.7	1388.7	1082.1	**768.4**	21649.2	17178.8
Fern	D_0	**6.0**	10.3	138.3	297.6	775.3	580.4
Grass	H	**9.3**	20.1	193.1	409.4	89.0	73.7
Herb	H	**848.8**	1387.7	1276.1	1089.1	1076.6	1120.8
Fern	H	**2.7**	10.3	168.7	256.4	65.3	7.5

Table 4. Results of the regression analysis for RSR with size parameters (diameter at the ground surface [D_0], height [H], and D_0^2H) by a power function ($y = ax^b$) among plant groups. Regressions with asterisks are significant (P<0.05) and ns means not significant (P>0.05).

Plant group	Independent variable (x) D_0, H, D_0^2H	a	b	Adjusted R^2
Grass	D_0 (cm)	0.78	0.04	ns
Herb	D_0 (cm)	0.57	0.26	0.42*
Fern	D_0 (cm)	0.87	0.32	0.54*
Grass	H (cm)	0.63	0.05	ns
Herb	H (cm)	0.10	0.38	0.32*
Fern	H (cm)	0.34	0.20	0.19*
Grass	D_0^2H (cm^3)	0.73	0.02	ns
Herb	D_0^2H (cm^3)	0.36	0.10	0.42*
Fern	D_0^2H (cm^3)	0.54	0.12	0.49*


a
AGB (g)
D0 (cm)
Grass
Herb
Fern
b
AGB (g)
Height (cm)
c
AGB (g)
D0²H (cm³)


a
BGB (g)
10000
1000
100
10
1
0.1
0.01
0.0
0.1
1.0
10.0
100.0
D0 (cm)
Grass
Herb
Fern
b
Height (cm)
1
10
100
1000
c
0.01
1
100
10000
1000000
D0^2H (cm^3)



10
a
RSR
1
0.1
0.0
0.1
1.0
10.0
100.0
Grass
Herb
Fern
D0 (cm)
10
b
RSR
1
0.1
1
10
100
1000
H (cm)
10
c
RSR
1
0.1
0.01
1
100
10000
1000000
D02H (cm3)