Allometric equations for estimating the aboveground biomass of bamboos in northern Laos

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ABSTRACT

Bamboos are dominant plants in northern Laos, where they are closely associated with local people's livelihoods. We developed species-specific allometric equations for estimating aboveground biomass from culm size parameters (diameter at breast height [DBH] and DBH^2H; H is a culm length) using 11 common bamboo species in the region. The applicability of multi-species allometric equations based on pooled data was also examined. Most species-specific allometric regressions showed significant correlations. In addition, the multi-species allometric relationships for culm biomass and aboveground biomass showed particularly high correlations ($r^2 > 0.96$), indicating the usefulness of multi-species allometric equations to estimate bamboo biomass in mixed-species bamboo forests with unknown bamboos and bamboos without species-specific allometric equations. The generally small differences in the fitness of aboveground biomass estimates between DBH and DBH^2H indicate that DBH is a practical explanatory variable for biomass estimation. These species-specific and multi-species allometric equations will help developing future work on carbon stocks and cycles in bamboo forests in this region.

KEYWORDS Allometry; carbon stocks; culm; fallow; multi-species relationship

Introduction

Recent reviews have demonstrated that bamboos have high potential to store substantial amounts of carbon due to their wide distribution and rapid growth rates (Nath et al. 2015; Yuen et al. 2017). Although approximately 100 studies have developed allometric equations to estimate bamboo biomass, most of these studies were conducted in China, Taiwan, and India (Yuen et al. 2017). As bamboo species and their physical traits differ regionally, the exploration of allometric relationships in research-scarce regions could contribute to the global evaluation of bamboo ecosystems.

In northern Laos, bamboos are common and widely distributed in fallow forests at early successional stages (Kiyono et al. 2007), which are major land-cover type in the region (Inoue et al. 2010). As bamboos play significant roles in the daily lives of local people as materials and foods (Roder et al. 1995; Ohno et al. 2008), useful bamboos have been planted and cultivated near villages. Consequently, bamboos are dominant plants and prominent components of landscapes in the region (Roder et al. 1997; Kameda and Nawata 2017). Nevertheless, little attention has been paid to the biomass or carbon accumulation of bamboos and only a few studies have proposed allometric equations for estimating bamboo biomass in northern Laos (Kiyono et al. 2007; Hirota et al. 2008). Although Hirota et al. (2008) examined four medium-sized bamboo species and Kiyono et al. (2007) studied mixed species in *Bambusa* and *Cephalostachyum*, the allometric relationships of the other bamboo species must be considered for a comprehensive understanding of bamboo biomass in the region.

Almost all of the existing allometric equations for bamboos have been species-specific (Yuen et al. 2016, 2017). The development of species-specific equations is ideal for the accurate estimation of biomass, but this is unlikely to be accomplished for all of the bamboo species. To facilitate the estimation of bamboo biomass/carbon in the region, it would be worthwhile to develop the multi-species allometric equations, which are reasonably applicable to any bamboo species.

The objectives of the present study were to (1) develop species-specific allometric equations for estimating the aboveground biomass and height of 11 common and widely distributed bamboo species in northern Laos, (2) develop multi-species allometric equations using pooled data for these 11 species, and (3) examine the applicability of the multi-species allometric relationship by comparing relationships among previously reported species-specific equations in the region.

Materials and Methods

Study sites

The study was mainly conducted in fallow forests near seven villages in three provinces in northern Laos (Table 1, Suppl. Fig. 1). Fallow is a major component of the landscapes around the villages and is often dominated by bamboos and early successional trees (Roder et al. 1997; Kameda and Nawata 2017). All areas had a tropical monsoon climate with an approximately 6-month dry season from October to March. The annual mean rainfall and temperature during 2012−2016 were 1487.1−1639.6 mm and 24.1−26.6 ºC, respectively (province-based data; DMH 2017). The soils were mainly acrisols, with some luvisols near Pak Bak village and alisols near the villages Huay Khot and Hat Ye (district-based data; SSLCC 2010).

Bamboo species and biomass measurement

We selected 11 bamboo species, that are often used by local people (Table 1, Suppl. Table 1, Suppl. Fig. 2). Of these species, seven are widely distributed in northern Laos (recorded in more than six of eight provinces) and the other four species (*Loi*, *Khao Lam*, *Phai Ban*, and *Puak*) have been observed in 3−4 provinces (Singkone et al. unpublished data). The species were identified at Kasetsart University, Thailand, and consisted of small to large species, i.e., with mean diameter at breast height (DBH; 1.3 m) ranging from 0.99 to 12.53 cm, three monopodial branching types, and eight sympodial types (Table 1). The spelling of local names follows that of ISO 11940-2.

For each species, 10 samples (one to three culms per clump) that differed in size were randomly harvested from neighboring clumps from November 2017 to January 2018. We used naturally grown bamboos in fallow forests, and well-developed cultivated bamboos near a banana orchard (×*Thyrsocalamus liang* [local name *Sang Phai*]) and teak plantation (*Thyrsostachys siamensis* [*Huak*]). After harvesting, we measured DBH (cm), culm length (H; m), and fresh weights of the culm, branches, and leaves in the field. To determine the ratio of dry weight to fresh weight, representative samples of each organ from each sample were oven-dried at 80 ºC for 72 h and weighed in the laboratory. The sum of the biomass of the culm, branches, and leaves was considered the aboveground biomass (AGB; kg).

We developed species-specific allometric equations between components and size variables using the standard allometric equation $y = ax^b$, where y is the culm length (H) or biomass of the culm, branches, leaves, and AGB (kg), x is DBH (cm) or DBH^2H (cm^2 m), and a and b are coefficients estimated by the regression. Multi-species allometric equations were also developed using the pooled data of 11 bamboo species. To assess the applicability of the resulting multi-species equations, we compared the allometric relationships with those derived from species-specific equations reported by Hirota et al. (2008) for four common bamboos in northern Laos: *Oxytenanthera parvifolia* (local name *Sot*), *Cephalostachyum virgatum* (*Hia*), *Bambusa tulda* (*Bong*), and *Indosasa sinica* (*No Khom*). The first two species correspond to *Gigantochloa scortechinii* and *Schizostachyum virgatum*, respectively, after revision of the scientific names (Singkone et al., unpublished data). Although the local name of *I. sinica* should be *Khom* under ISO 11940-2, we used *No Khom* due to its high familiarity. The allometric relationships were assessed using the standardized major axis (SMA) method after log-transformation of both variables (Warton et al. 2006, 2012). All statistical analyses were performed using the software package R ver. 3.0.2 (R Core Team 2013).

Results

Species-specific allometric relationships

Most of the species-specific allometric regressions for the biomass of plant components and AGB showed significant correlations (Table 2). Although the allometric relationships for culm length and biomass of branches or leaves in four species (*Indosasa* sp. 1, *Fargesia* sp. 1, *Dendrocalamus hamiltonii*, and *Dendrocalamus sinicus*) had low correlations, all of the allometric equations for

AGB had significant correlations, except for *Fargesia* sp. 1 as a function of DBH^2H. The fitness of the equations was greater when DBH^2H was used as the explanatory variable in some relationships, whereas more fitted estimates were obtained by using DBH in others, although the differences were generally small (Table 2).

Multi-species allometric relationships

We found relatively high correlations ($r^2 > 0.77$) for all equations using the pooled data of 11 bamboo species (Table 2, Fig. 1). Multi-species allometric relationships for culm biomass and AGB had particularly high correlations ($r^2 > 0.96$). The difference in the fitness of the estimates using DBH and DBH^2H as the explanatory variable was small (Table 2). Compared to the AGBs obtained with species-specific allometric equations by Hirota et al. (2008), the AGB calculated by our multi-species allometric equation was somewhat overestimated or underestimated, depending on the bamboo species (Fig. 2).

Discussion

Species-specific allometric equations of significant fitness were obtained to estimate AGB for 11 bamboo species in northern Laos. Using our models together with those in Hirota et al. (2008), the species-specific AGB of many common bamboos in the region can now be estimated. The multi-species allometric equations also had sufficiently high correlations, particularly for culm biomass and AGB, indicating the applicability of the equations to various bamboos in northern Laos irrespective of species, size, and branching type. The difference in AGBs estimated by species-specific and multi-species allometric equations is unavoidable because the former equations normally lead to more accurate biomass quantification of the specific bamboo species. However, multi-species allometric equations are useful when evaluating bamboo biomass in mixed-species bamboo forests with unknown bamboos and bamboos without species-specific allometric equations.

The allometric relationships between branch and leaf biomass and bamboo size (using both DBH and DBH^2H) generally showed greater variation than those for culm biomass and AGB in both the species-specific and multi-species models. Similar patterns have often been observed in other bamboos (Isagi et al. 1997; Nath et al. 2009; Yen et al. 2010; Chan et al. 2013). The branching pattern can be largely affected by habitat conditions, such as light, clump crowding, and culm position within a clump. Because long and slender tips of culms often droop and the amount of branches and leaves on curved culms could vary from that on straight ones, bent-tipped culms are another possible reason for the large variation observed in this study. Curved culms may also have led to lower fitness in some equations when DBH^2H was used as the explanatory variable, since we measured culm length after harvesting as the culm height (H) and the H values might be overestimated. Considering the generally small difference in fitness between equations using DBH and DBH^2H and the difficulty of obtaining height and length by the measurements without destructive sampling, DBH is a practical, easily measured explanatory variable for field estimation of bamboo biomass (Yen et al. 2010).

In this study, we developed species-specific and multi-species allometric equations for 11 major bamboo species in northern Laos. Species-specific allometric equations are preferable to accurately estimate the biomass of each bamboo species. Furthermore, given the high biodiversity of bamboos, the difficulty of identifying bamboo species at the site, and the sympatric distribution of multiple bamboo species in the region, the developed multi-species allometric equations prove useful in further studies evaluating biomass and carbon stocks/cycles in bamboo forests.

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Disclosure statement

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Table 1. Morphological traits and sampling sites of the 11 bamboo species.

Local name	Scientific name	DBH (cm)	Thickness of culm wall (mm)*	Internode length (cm)*	H (m)	Clump type	Sampling site		
							Province	Village	Altitude (m)
Kham Lao	*Phyllostachys lithophila*	0.99	2.07	15.48	3.03	monopodial	Xayabouly	Mok Satu	783
Lan	*Indosasa* sp.1	1.24	3.36	49.98	3.66	monopodial	Luang Prabang	Pak Bak	520
Loi	*Fargesia* sp.1	2.10	2.05	38.65	9.32	monopodial	Luang Prabang	Pak Bak	520
Lai	*Gigantochloa albociliata*	2.58	7.90	30.88	7.73	sympodial	Xayabouly	Huay Pet	272
Khao Lam	*Cephalostachyum pergracile*	3.93	10.57	39.39	10.42	sympodial	Xayabouly	Na La	315
Huak	*Thyrsostachys siamensis*	5.07	9.67	18.91	11.71	sympodial	Luang Prabang	Huay Khot	425
Sang Phai	*×Thyrsocalamus liang*	5.39	15.26	23.28	13.90	sympodial	Luang Prabang	Huay Khot	425
Sang	*Dendrocalamus membranaceus*	5.91	11.40	28.47	14.77	sympodial	Luang Prabang	Huay Khot	425
Phai Ban	*Bambusa blumeana*	6.73	13.50	25.41	17.35	sympodial	Xayabouly	Na Kaeng Ma	270
Hok	*Dendrocalamus hamiltonii*	7.64	10.40	40.25	16.37	sympodial	Luang Prabang	Pak Bak	520
Puak	*Dendrocalamus sinicus*	12.53	18.41	20.16	17.08	sympodial	Xieng Khouang	Hat Ye	1154

*The internode length and thickness of culm wall were measured at 1.3m height.

Table 2. Results of SMA regression analyses for estimating bamboo biomass and height ($y = ax^b$) using species-specific and polled data.

Species (local name)	Allometry	*a*	*b*	r^2		Allometry	*a*	*b*	r^2	
Phyllostachys lithophila	DBH-H	3.0400	1.1006	0.6545						
(*Kham Lao*)	DBH-Culm	0.0635	2.5947	0.6167		DBH^{2}H-Culm	0.0241	0.8758	0.6151	
	DBH-Branch	0.0582	2.1731	0.5356		DBH^{2}H-Branch	0.025	0.7335	0.6358	
	DBH-Leaf	0.1001	3.8078	0.2766	n.s.	DBH^{2}H-Leaf	0.024	1.2853	0.3186	n.s.
	DBH-AGB	0.2329	2.7768	0.5988		DBH^{2}H-AGB	0.082	0.9372	0.6402	
Indosasa sp.1	DBH-H	3.0560	0.8385	0.1163	n.s.					
(*Lan*)	DBH-Culm	0.0676	2.2212	0.3861	n.s.	DBH^{2}H-Culm	0.022	0.9254	0.4708	
	DBH-Branch	0.0239	3.1934	0.3291	n.s.	DBH^{2}H-Branch	0.004	1.3305	0.3868	n.s.
	DBH-Leaf	0.0299	2.6426	0.0177	n.s.	DBH^{2}H-Leaf	0.007	1.1011	0.0224	n.s.
	DBH-AGB	0.1444	1.8700	0.4680		DBH^{2}H-AGB	0.056	0.7791	0.5962	
Fargesia sp.1	DBH-H	15.3533	-0.7108	0.0002	n.s.					
(*Loi*)	DBH-Culm	0.1436	1.8672	0.7234		DBH^{2}H-Culm	0.021	0.8827	0.4984	
	DBH-Branch	0.0464	1.5741	0.1506	n.s.	DBH^{2}H-Branch	0.009	0.7441	0.0498	n.s.
	DBH-Leaf	0.0285	1.6949	0.0008	n.s.	DBH^{2}H-Leaf	0.554	-0.8012	0.0092	n.s.
	DBH-AGB	0.2708	1.5196	0.6398		DBH^{2}H-AGB	0.058	0.7183	0.3965	n.s.
Gigantochloa albociliata	DBH-H	2.2010	1.3074	0.7522						
(*Lai*)	DBH-Culm	0.0648	2.6163	0.9255		DBH^{2}H-Culm	0.031	0.8174	0.8509	
	DBH-Branch	0.0336	2.9330	0.8517		DBH^{2}H-Branch	0.014	0.9163	0.7653	
	DBH-Leaf	0.0173	2.5315	0.7189		DBH^{2}H-Leaf	0.008	0.7909	0.6628	
	DBH-AGB	0.1198	2.6803	0.9022		DBH^{2}H-AGB	0.057	0.8373	0.8216	
Cephalostachyum pergracile	DBH-H	3.1385	0.8782	0.6283						
(*Khao Lam*)	DBH-Culm	0.1859	2.0056	0.9173		DBH^{2}H-Culm	0.070	0.7301	0.8638	
	DBH-Branch	0.0195	2.4257	0.9266		DBH^{2}H-Branch	0.006	0.8830	0.9137	
	DBH-Leaf	0.0207	2.1861	0.7912		DBH^{2}H-Leaf	0.007	0.7958	0.8284	
	DBH-AGB	0.2399	2.0311	0.9469		DBH^{2}H-AGB	0.090	0.7393	0.9070	
Thyrsostachys siamensis	DBH-H	2.3573	0.9876	0.8157						
(*Huak*)	DBH-Culm	0.0255	3.1534	0.9135		DBH^{2}H-Culm	0.009	1.0781	0.9384	
	DBH-Branch	0.0376	1.6112	0.4133		DBH^{2}H-Branch	0.022	0.5509	0.3432	n.s.
	DBH-Leaf	0.0540	1.2069	0.6392		DBH^{2}H-Leaf	0.036	0.4126	0.6100	
	DBH-AGB	0.0685	2.6746	0.9131		DBH^{2}H-AGB	0.028	0.9144	0.9280	
×*Thyrsocalamus*	DBH-H	5.2202	0.5832	0.6085						

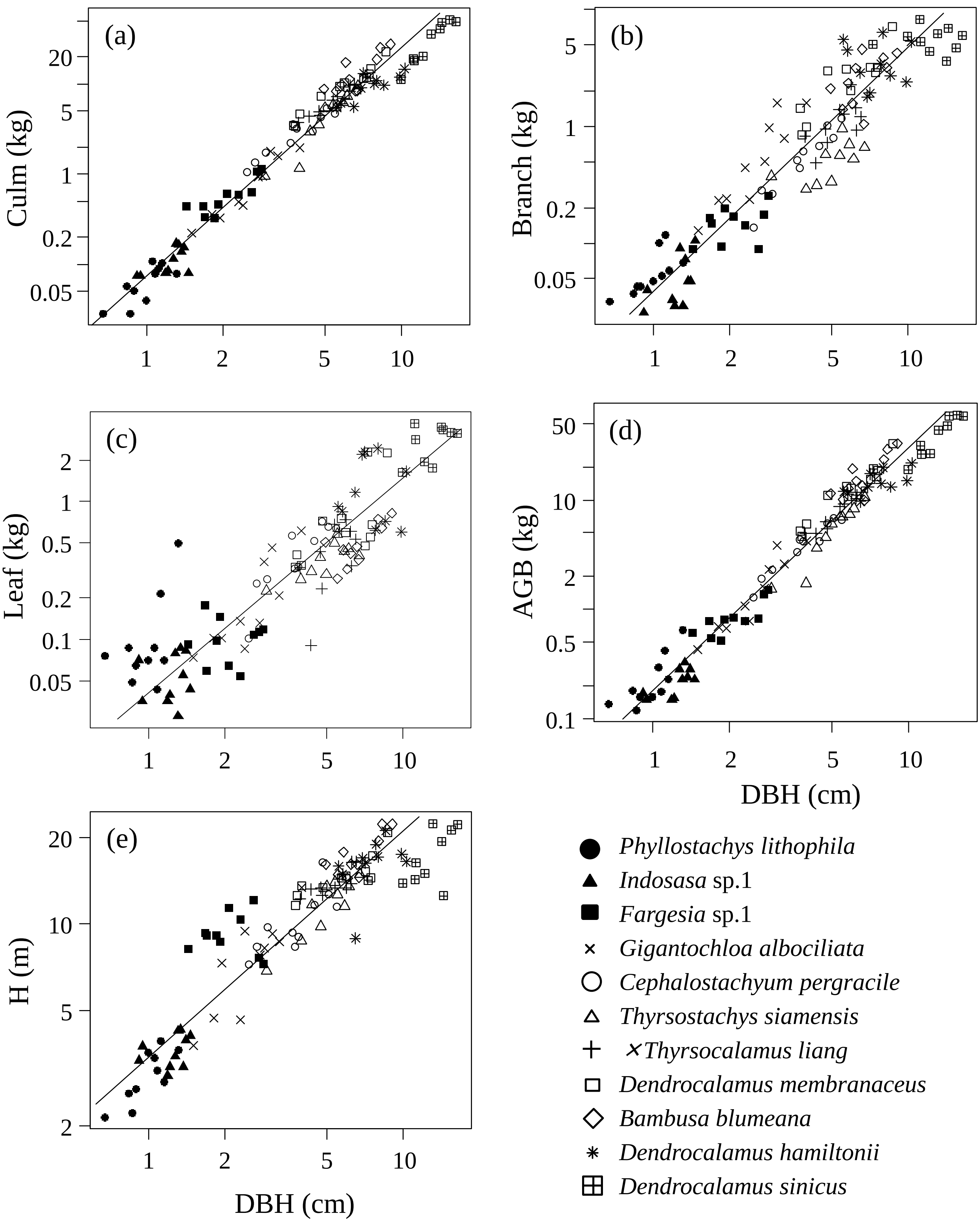
liang (*Sang Phai*)	DBH-Culm	0.2112	2.0312	0.9437		DBH^2H-Culm	0.047	0.8179	0.9778	
	DBH-Branch	0.0163	2.4963	0.4403		DBH^2H-Branch	0.002	1.0052	0.3374	n.s.
	DBH-Leaf	0.0008	3.7185	0.3669	n.s.	DBH^2H-Leaf	0.000	1.4973	0.2954	n.s.
	DBH-AGB	0.2754	2.0037	0.9456		DBH^2H-AGB	0.063	0.8068	0.9354	
Dendrocalamus membranaceus (*Sang*)	DBH-H	5.8316	0.5285	0.7525						
	DBH-Culm	0.2379	2.0623	0.9608		DBH^2H-Culm	0.050	0.8339	0.9736	
	DBH-Branch	0.0651	2.0640	0.7649		DBH^2H-Branch	0.013	0.8346	0.7736	
	DBH-Leaf	0.0282	1.7659	0.4990		DBH^2H-Leaf	0.007	0.7141	0.5675	
	DBH-AGB	0.3634	1.9938	0.9360		DBH^2H-AGB	0.081	0.8062	0.9516	
Bambusa blumeana (*Phai Ban*)	DBH-H	3.4090	0.8544	0.6066						
	DBH-Culm	0.1144	2.5037	0.6466		DBH^2H-Culm	0.029	0.9200	0.7010	
	DBH-Branch	0.0166	2.6474	0.3036	n.s.	DBH^2H-Branch	0.003	0.9728	0.3914	n.s.
	DBH-Leaf	0.0145	1.8460	0.5561		DBH^2H-Leaf	0.005	0.6783	0.6856	
	DBH-AGB	0.2178	2.2806	0.6945		DBH^2H-AGB	0.063	0.8380	0.7637	
Dendrocalamus hamiltonii (*Hok*)	DBH-H	1.7335	1.1048	0.1806	n.s.					
	DBH-Culm	0.2766	1.7389	0.7102		DBH^2H-Culm	0.108	0.6531	0.7457	
	DBH-Branch	271.9383	-2.1816	0.0046	n.s.	DBH^2H-Branch	885.173	-0.8193	0.0032	n.s.
	DBH-Leaf	256.8970	-2.6767	0.0018	n.s.	DBH^2H-Leaf	1093.082	-1.0053	0.0087	n.s.
	DBH-AGB	1.2130	1.2249	0.4688		DBH^2H-AGB	0.625	0.4600	0.5196	
Dendrocalamus sinicus (*Puak*)	DBH-H	1.7615	0.8989	0.3358	n.s.					
	DBH-Culm	0.0555	2.4642	0.8398		DBH^2H-Culm	0.017	0.9386	0.8142	
	DBH-Branch	64.5929	-0.9854	0.0034	n.s.	DBH^2H-Branch	103.302	-0.3753	0.0227	n.s.
	DBH-Leaf	0.1154	1.2477	0.1805	n.s.	DBH^2H-Leaf	0.063	0.4752	0.1196	n.s.
	DBH-AGB	0.3093	1.8972	0.8226		DBH^2H-AGB	0.125	0.7226	0.7808	
11 spp total	DBH-H	3.4575	0.7845	0.8476						
	DBH-Culm	0.0748	2.5356	0.9670		DBH^2H-Culm	0.022	0.9256	0.9766	
	DBH-Branch	0.0389	2.0874	0.8814		DBH^2H-Branch	0.014	0.7619	0.8781	
	DBH-Leaf	0.0410	1.5597	0.8024		DBH^2H-Leaf	0.019	0.5693	0.7719	
	DBH-AGB	0.1794	2.2214	0.9668		DBH^2H-AGB	0.062	0.8109	0.9671	

n.s., not significant

Figure legends

Figure 1. Allometric relationships between diameter at breast height (DBH) and (a) culm biomass, (b) branch biomass, (c) leaf biomass, (d) aboveground biomass (AGB), and (e) culm length (H) for 11 bamboo species in northern Laos. The regression lines for the pooled data are shown.

Figure 2. Comparison of AGB estimated by the developed multi-species allometric equation with those derived from species-specific equations (Hirota et al. 2008).



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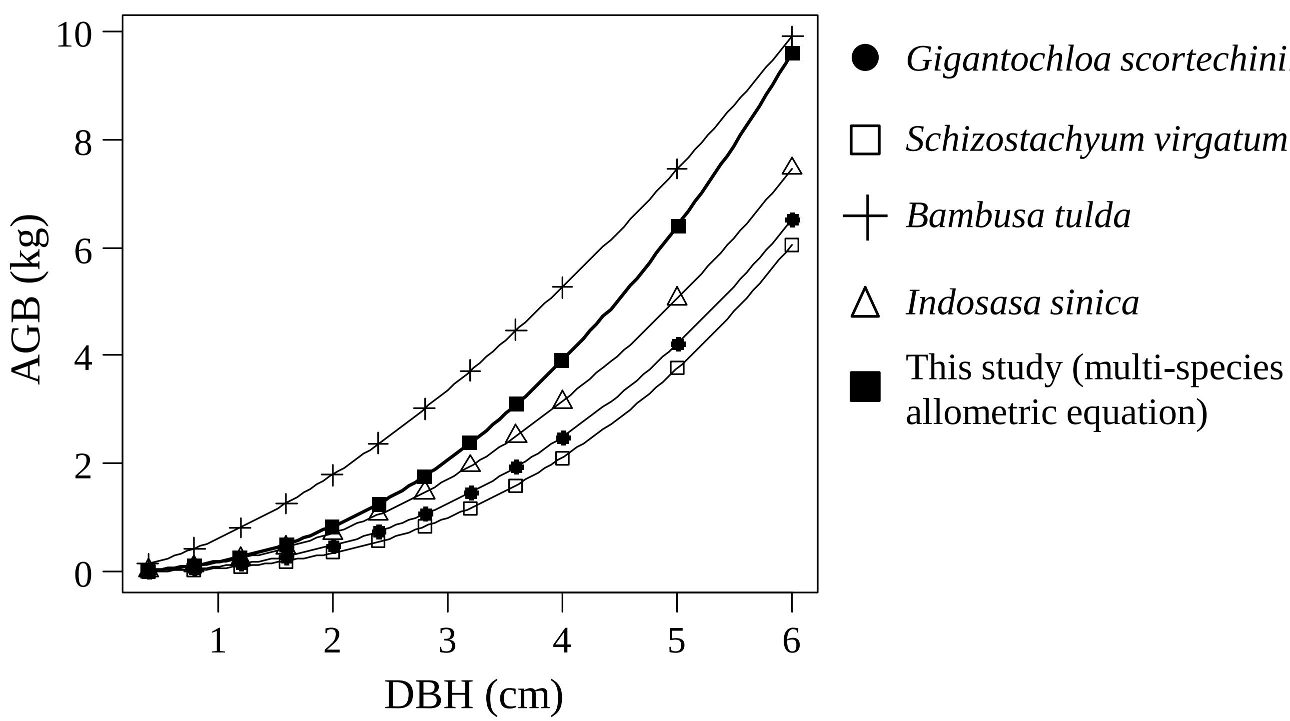

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