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Original article

Allometric Equations for Estimating the Aboveground Biomass of a 14-Year-Old Bamboo Plantation at Moeswe Research Station, Myanmar

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ABSTRACT

Due to depletion of bamboo resource, the local population in Myanmar is taking initiatives on raising bamboo in their homesteads and in small commercial plantations to guarantee a continuous bamboo supply. In this study, the aboveground biomasses of 10 commercially important bamboo species planted in the bamboo demonstration plot at the Moeswe Research Station, Naypyitaw, Myanmar. Destructive sampling method was used to determine the relationships between biomasses of leaf, branch, stem, culm, and a fundamental variable of growth (diameter at breast height or DBH). For an easier estimation of the aboveground biomass (AGB) of a clump, a relationship between the number of culms per clump and the AGB of a clump was also developed. However, the AGB was over- or under-estimated when the clump biomass models were employed. Therefore, AGB of the culm was calculated using the best-fit power and exponential models in which DBH was used as an independent variable.

The sampled clumps were randomly selected for estimating the AGB of 10 bamboo species. The AGB of a sampled clump was calculated by summing the AGB of the culms in a clump. The AGB of different bamboo species were found to be statistically different at $p<0.05$. *Bambusa* sp. (109.38 t ha^{-1}) had the highest AGB followed by *Dendrocalamus brandisii* (79.72 t ha^{-1}), *Bambusa nutans* (73.89 t ha^{-1}), *Bambusa tulda* (59.10 t ha^{-1}), *Bambusa vulgaris* (54.69 t ha^{-1}), *Dendrocalamus strictus* (40.71 t ha^{-1}), *Thyrsostachys siamensis* (31.90 t ha^{-1}), *Bambusa polymorpha* (23.05 t ha^{-1}), *Dendrocalamus longispathus* (16.66 t ha^{-1}) and *Cephalostachyum pergracile* (14.22 t ha^{-1}). The AGB was contributed by both the number of culms per clump and the DBH of the culms. With regard to the raising bamboo, *Bambusa* sp. is the most preferable species owing to a highest number of culms per clump and highest AGB.

Keywords: Bamboos, Allometric equations, Aboveground biomass, Moeswe research station, Myanmar

INTRODUCTION

Myanmar is the second largest country in ASEAN, with a total land area of 67.66 million ha. The country is rich in bamboo resources, with almost 41% of the land under bamboo cover (Food and Agricultural Organization, 2005). According to a checklist prepared by Kress *et al*. (2003), Myanmar has 23 genera and 102 bamboo species. Generally, bamboo is found in three broad regions of the country: the Rakhine Range in the west, the Bago Range in the center, and the Shan hills towards the east.

Rapid growth and maturity of bamboo culms and their short rotation cycles give bamboo an advantage over timber when it comes to generating cash for farmers (Business Innovation Facility, 2015a). As such, the bamboo resources have been diminishing gradually over the years in areas where the domestic needs and market demand for bamboo are high. According to the population census of 2014, Myanmar's population increased from 35.31 million in 1983 to 51.42 million in 2014 (Ministry of Immigration and Population, 2015). Over 1.6 billion people are living in extreme poverty and 70% of the population is dependent on non-timber forest products (NTFPs) for their basic needs and income (Wasiq and Ahmad, 2004). Among the various NTFPs, bamboo plays a vital role in Myanmar's society. The bamboo shoot is used as a food source and the culm is used for construction, handicrafts, household goods, pulp, and flooring (Business Innovation Facility, 2015a).

Among the 102 bamboo species in Myanmar, some species are recognized for their economic value to the society. The local market price of raw bamboo culm ranges from 150 to 1,500 kyats depending on the bamboo species, size (diameter and height), and the end market use. According to Food and Agricultural Organization's report of 2005, the annual bamboo consumption for wood and fuel had risen from 7,752,000 tons in 1990 to 9,803,000 tons in 2005.

At present, the majority of market demand and domestic needs for bamboo is fulfilled by harvesting it from natural bamboo forests. High levels of competition for bamboo resources, over harvesting of the resource from natural forest, and lack of proper management have resulted in the depletion of resources, reducing the size and quality of bamboo. The Business Innovation Facility (2015a; b) strongly recommended the effective management of reserves or for a plantation or community forest based approach for a sustained supply of bamboo resources.

State or privately owned plantations have been encouraged in Myanmar, according to the National Forest Policy 1995 (Ministry of Natural Resources and Environmental Conservation, 1995; Ministry of Natural Resources and Environmental Conservation, 2006). Due to its rapid biomass accumulation and effective fixation of solar energy and carbon dioxide, the carbon sequestration ability of bamboo is likely to be second to none (Fu, 2007). However, not much work has been done on estimating the biomass of bamboo in Myanmar. Fukushima *et al.* (2007) and Chan *et al*. (2013) have estimated the aboveground biomass of some bamboo species in stands from a current swidden field to fallow areas at different ages. Chan *et al*. (2013) suggested that site-specific allometric relationships should be developed for accurate estimation of biomass in tropical forests. Hnin (2017) investigated the aboveground biomass (AGB) of *Bambusa polymorpha*, *Cephalostachyum pergracile*, and *Dendrocalamus longispathus* under different clump management trials in a bamboo demonstration plot in Myanmar.

Despite the growing interest in establishing bamboo plantations in Myanmar, study on the growth of bamboo species in terms of biomass has been limited and consequently, there is little to no information available to encourage potential growers about bamboo biomass production. In this study, site specific models were developed and the AGB of 10 bamboo species was investigated, with particular emphasis on the bamboo plantation established at Moeswe Research Station, Naypyitaw in Myanmar in 2003. The study can benefit the estimation of biomass production and choice of bamboo species to a potential bamboo grower in the reference region.

MATERIALS AND METHODS

Study Area

The study area is a bamboo plantation situated at Moeswe Research Station, Ngalaik Reserved Forest, Okttrathiri Township, Okttra District, Naypyitaw, Myanmar. The study site is situated at 181-227 m above sea level at a latitude of 19º 56’ N and longitude of 95º 56’ E. The soil in the study site is of a sandy loam texture and slightly acidic, with the pH varying from 5.76 to 6.77. The study area has an average annual rainfall of 1,167 mm. The mean maximum temperature ranges from 29.1º C (December) to 38.1º C (April) while the mean minimum temperature ranges from 14.4º C (January) to 24.6º C (April).

The 25-hectare-bamboo plantation was established in 2003 in a mixed deciduous forest where common non-teak hardwood species grow naturally (International Tropical Timber Organization, 2003). According to the International Tropical Timber Organization (2007), *Bambusa polymorpha*, *Bambusa tulda*, *Cephalostachyum pergracile*, *Dendrocalamus brandisii*, *Dendrocalamus hamiltonii*, *Dendrocalamus longispathus*, *Dendrocalamus strictus*, *Dinochloa maclellandii*, *Oxytenanthera nigrociliata*, and *Thyrsostachys siamensis* were planted at 4.5 × 4.5 m spacing under the forest canopy. Among these 10 species, *D. hamiltonii*, *D. maclellandii* and *O. nigrociliata* were not found during the present investigation. In many cases, *D. brandisii* is misidentified as *D. hamiltonii* based on some culm characteristics. Investigating *Bambusa nutans*, *Bambusa vulgaris*, and some “*Bambusa*” clumps, which were not reported in the International Tropical Timber Organization’s project report, another possible reason could be that all the clumps of *D. hamiltonii*, *D. maclellandii*, and *O. nigrociliata* could have died and replaced by another species.

At present, the bamboo plantation occupies an area of nearly 19 ha and the study investigated 10 species. Among these species, only the genus of one bamboo could be identified and was referred to as “*Bambusa* sp.” Based on field observations, *Bambusa* sp. showed characteristics which were similar to those of *B. tulda*, such as branch complement, position, and size of auricles and culm hairs. In *B. tulda*, branches can be found all along the length of the culm. However, the fact that branches of *Bambusa* sp. were found only in the upper part of the culm reduced the confidence in species identification. Therefore, it was referred to as "*Bambusa* sp." in the present study.

Data Collection

Sampling for AGB estimation

In the study area, 279 bamboo clumps (sampling intensity = 3.30%) were randomly selected and measured for the number of culms and diameter at 130 cm above the ground (diameter at breast height or DBH) of all the culms in a sampled clump. In the case of *D. strictus*, the culms were congested and the whole culm was densely covered with branches. The culms in the inner part of a clump could not be reached for the purpose of measuring their DBHs. Therefore, the diameter range of the species was determined by randomly measuring different sizes of a few culms from different clumps. Each DBH was allocated to one of three diameter classes (0.1-2.0 cm, 2.1-4.0 cm, and 4.1-6.0 cm). The number of culms was binned into the corresponding diameter class.

Destructive sampling for development of height-diameter models and biomass models

Six DBH classes were constructed to represent the complete DBH range of each species. Three culms from each diameter class (18 culms for each bamboo species), which were free from defects and tortuosity, were selected for felling. In total, 180 culms were felled for the 10 species. The sampled culms were cut at ground level and the DBH and height (H) of each culm were measured. The stem, branch, and leaf were separated, and their fresh weights were weighed separately using a digital hanging balance (Portable LCD Electronic Digital Hanging Luggage Weight). The total fresh weight of a culm was calculated by summing the fresh weights of the stem, branch, and leaf.

In each sampled culm, five sub-samples were taken, out of which three sub-samples were of the base, mid and top part of stem, one of branch and one of leaf, respectively. Each sub-sample was weighed immediately using a chemical scale (SUNFORD KAH5000) and the fresh weight was determined. Each sub-sample was placed in a separate poly bag and sent to the laboratory at the Forest Research Institute, Yezin, Myanmar. The sub-samples were dried at 70°C until a constant weight was reached as measured by the chemical scale.

Data Analysis

Regression analysis for height-diameter models

H and DBH are often used as the independent variables in biomass estimation models. However, the curved nature of a bamboo culm at its tip makes the physical measurement of the total culm height harder and time consuming than determining the DBH. Therefore, a regression analysis was used to predict the height of a culm using the values of DBH recorded from destructive sampling.

The relationship between DBH and H was tested using linear, logarithmic, power, and exponential models, among which, the model which provided the highest adjusted coefficient of determination (Adj. R^2) and standard error of estimate (SEE) was chosen to predict the value of H for the culm of a given species.

Regression analysis for culm component biomass models

The dry weights of stem, branch, leaf, and of a whole culm were calculated using the data collected from harvested culms and their corresponding sub-samples, which in turn were used to develop mathematical equations. Regression analysis was performed using values of total dry weight (TDW) from harvested bamboo culms (n = 180) using the IBM SPSS Statistics 22.0 (for Windows) software package. Regression models (linear, logarithmic, quadratic, power, and exponential) were used to analyse the relationship between the dry weight of the sampled culms and the independent variables (DBH and H). A preliminary analysis of the proposed models was conducted using different combinations of independent variables such as DBH (cm), H (m), DBH H (cm m), DBH^2 H (cm^2 m), and DBH H^2 (cm m^2).

Regression analysis for clump biomass models

Using the models to estimate culm biomass, the AGB of a culm was calculated. The AGB values of sampled clumps (279 in total) of the 10 species were calculated by summing the AGB of culms in a clump. Among the sampled clumps, eight clumps were selected in each species, based on culms representing the complete DBH range and the range in the number of culms per clump. Regression analysis (linear, logarithmic, power, and exponential) was then performed using the number of culms per clump as an independent variable to estimate the AGB of the clump for each species.

Biomass determination

The AGB of the species was estimated using the best-fit allometric models developed. Analysis of variance (ANOVA) and post-hoc analysis (Bonferroni) were performed to determine significant difference in terms of the AGB among the 10 bamboo species.

RESULTS AND DISCUSSION

Models for Estimating the Height of a Culm

The highest adjusted R^2 and lowest SEE values were obtained for the power model ($y=ax^b$) for eight species, specifically *B. polymorpha*, *B. nutans*, *B. tulda*, *Bambusa* sp., *C. pergracile*, *D. brandisii*, *D. longispathus*, and *T. siamensis*. The remaining two species, *B. vulgaris* and *D. strictus*, were better represented by an exponential relationship ($y=ae^{bx}$) between DBH and H (a and b are the regression coefficients, indicated in Table 1).

Table 1 Models for estimating the culm height of 10 bamboo species.

Species	Model	Adj. R^2 value	SEE	P-value
B. nutans	$y=4.981\ DBH^{0.583}$	0.885	0.086	0.000
B. polymorpha	$y=3.480\ DBH^{0.727}$	0.910	0.110	0.000
B. tulda	$y=6.078\ DBH^{0.381}$	0.571	0.138	0.000
B. vulgaris	$y=4.451\ e^{0.157\ DBH}$	0.778	0.158	0.000
Bambusa sp.	$y=4.058\ DBH^{0.643}$	0.762	0.151	0.000
C. pergracile	$y=3.586\ DBH^{0.792}$	0.842	0.185	0.000
D. brandisii	$y=3.488\ DBH^{0.620}$	0.853	0.123	0.000
D. longispathus	$y=3.579\ DBH^{0.762}$	0.889	0.137	0.000
D. strictus	$y=4.557\ e^{0.182\ DBH}$	0.820	1.024	0.000
T. siamensis	$y=2.971\ DBH^{0.813}$	0.787	0.163	0.000

Remark: y=Height of a culm (m).

Models for Estimating the Biomass of Culm Components and AGB

All models resulted in significant relationships between the growth parameters (DBH and H of culm) and biomass. For *D. brandisii*, the exponential model was the best fit as indicated by the highest adjusted R^2 value (0.929). For the remaining nine species, excluding *D. brandisii*, power models that used DBH as the independent variable resulted in higher adjusted R^2 values. In the case of *B. tulda*, although the quadratic model using DBH^2 *H as the independent variable provided an adjusted R^2 value (0.977) which was as high as the power model using DBH alone, the power model was selected for its lower SEE value (0.150). Therefore, the power model, $y=ax^b$, and the exponential model, $y=ae^{bx}$, where y is the dry biomass (kg $culm^{-1}$), x is DBH (cm), and a and b are model coefficients, were used for estimating the biomass of the culm components and AGB of the culm as presented in Table 2 and Figure 1.

Compared with the models for stem biomass, biomass models for leaf and branch resulted in relatively low adjusted R^2 values. According to Nath *et al.* (2009) and Nath *et al.* (2015), the biomass of leaf, branch, and stem of some bamboo species varied significantly with the age of culms. However, variation in biomass between young and old culms is less in mature plantation (20 years) due to a well-developed rhizome system (Kaushal *et al*., 2016). As the present study was done in a mature plantation, not accounting for the age of culms during destructive sampling might have contributed to a lower adjusted R^2 values in the leaf and branch biomass models. However, the relationship between the biomass of leaf and branch components with the culm DBH was still significant.

Table 2 Models for estimating the biomass of culm components and AGB of a culm from culm DBH of ten bamboo species.

Species	Culm component	Biomass model	Adj. R^2 value	SEE	P<0.05
B. nutans	Stem	$y=0.120\ DBH^{2.554}$	0.980	0.149	0.000
	Branch	$y=0.037\ DBH^{2.383}$	0.854	0.402	0.000
	Leaf	$y=0.026\ DBH^{1.642}$	0.623	0.515	0.000
	Aboveground	$y=0.215\ DBH^{2.375}$	0.971	0.167	0.000
B. polymorpha	Stem	$y=0.113\ DBH^{2.183}$	0.967	0.194	0.000
	Branch	$y=0.049\ DBH^{1.453}$	0.718	0.436	0.000
	Leaf	$y=0.020\ DBH^{1.657}$	0.765	0.441	0.000
	Aboveground	$y=0.174\ DBH^{2.043}$	0.950	0.226	0.000
B. tulda	Stem	$y=0.186\ DBH^{2.295}$	0.983	0.124	0.000
	Branch	$y=0.078\ DBH^{2.022}$	0.765	0.473	0.000
	Leaf	$y=0.005\ DBH^{2.880}$	0.579	1.001	0.000
	Aboveground	$y=0.307\ DBH^{2.174}$	0.975	0.150	0.000
B. vulgaris	Stem	$y=0.138\ DBH^{2.326}$	0.983	0.136	0.000
	Branch	$y=0.144\ DBH^{1.431}$	0.716	0.398	0.000
	Leaf	$y=0.081\ DBH^{1.309}$	0.582	0.485	0.000
	Aboveground	$y=0.347\ DBH^{1.960}$	0.945	0.211	0.000
Bambusa sp.	Stem	$y=0.141\ DBH^{2.355}$	0.985	0.122	0.000
	Branch	$y=0.014\ DBH^{2.510}$	0.762	0.587	0.000
	Leaf	$y=0.007\ DBH^{2.531}$	0.810	0.515	0.000
	Aboveground	$y=0.164\ DBH^{2.385}$	0.969	0.181	0.000
C. pergracile	Stem	$y=0.109\ DBH^{2.263}$	0.979	0.178	0.000
	Branch	$y=0.089\ DBH^{1.266}$	0.710	0.434	0.000
	Leaf	$y=0.068\ DBH^{1.180}$	0.670	0.443	0.000
	Aboveground	$y=0.258\ DBH^{1.882}$	0.938	0.262	0.000
D. brandisii	Stem	$y=0.381\ e^{0.454\ DBH}$	0.943	0.261	0.000
	Branch	$y=0.268\ e^{0.359\ DBH}$	0.701	0.543	0.000
	Leaf	$y=0.194\ e^{0.268\ DBH}$	0.708	0.399	0.000
	Aboveground	$y=0.924\ e^{0.385\ DBH}$	0.929	0.249	0.000
D. longispathus	Stem	$y=0.141\ DBH^{1.971}$	0.918	0.300	0.000
	Branch	$y=0.041\ DBH^{1.915}$	0.827	0.445	0.000
	Leaf	$y=0.064\ DBH^{1.478}$	0.730	0.454	0.000
	Aboveground	$y=0.279\ DBH^{1.824}$	0.929	0.256	0.000
D. strictus	Stem	$y=0.171\ DBH^{2.416}$	0.972	0.174	0.000
	Branch	$y=0.104\ DBH^{1.818}$	0.747	0.448	0.000
	Leaf	$y=0.030\ DBH^{2.061}$	0.667	0.613	0.000
	Aboveground	$y=0.307\ DBH^{2.228}$	0.943	0.232	0.000
T. siamensis	Stem	$y=0.103\ DBH^{2.461}$	0.972	0.163	0.000
	Branch	$y=0.011\ DBH^{2.755}$	0.760	0.596	0.000
	Leaf	$y=0.020\ DBH^{2.038}$	0.680	0.537	0.000
	Aboveground	$y=0.156\ DBH^{2.372}$	0.920	0.272	0.000

Remark: y=Dry weight (kg $culm^{-1}$).

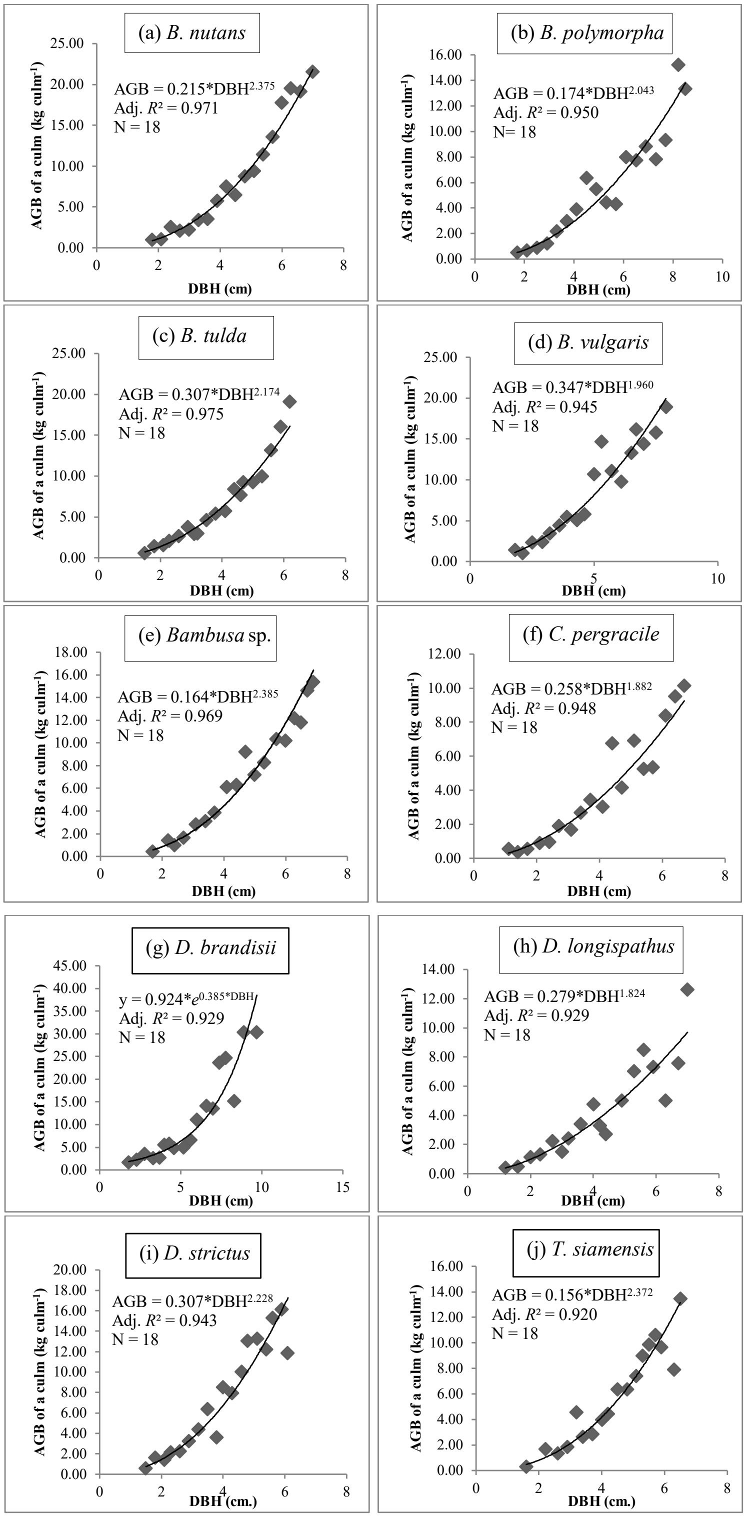

Figure 1 Relationship between DBH and AGB of culms of (a) *B. nutans*, (b) *B. polymorpha*, (c) *B.tulda*, (d) *B. vulgaris*, (e) *Bambusa* sp., (f) *C. pergracile*, (g) *D. brandisii*, (h) *D. longispathus*, (i) *D. strictus*, and (j) *T. siamensis* at the Moeswe Research Station.

Models for Estimating Clump Biomass

A power model ($y=ax^b$) using the number of culms per clump as an independent variable was found to be the best-fit for six species, namely *Bambusa* sp., *B. vulgaris*, *D. brandisii*, *D. longispathus*, *D. strictus*, and *T. siamensis*. For the remaining four species (*B. nutans*, *B. polymorpha*, *B. tulda*, and *C. pergracile*), the exponential model ($y=ae^{bx}$) had the highest adjusted R^2 and lowest SEE values. In the equations, y is the AGB of a clump (kg $clump^{-1}$), x is the number of culms per clump, and a and b are the model coefficients.

Among the sampled clumps used for developing models for the estimation of clump AGB, some clumps with a higher number of culms per clump had lower clump AGB values than those with lower number of culms per clump. Among the culms in a clump, a larger proportion of culms in the lower DBH classes indicated a lower clump AGB, although there were a higher number of culms per clump. It could be assumed that contribution to the clump AGB was both by the number of culms per clump and the DBH of the culms.

Clump biomass models, as presented in Table 3 and Figure 2, are useful when the time and budget for data collection is limited. However, the values of adjusted R^2 were markedly lower than the values obtained by the biomass models constructed for the culms. A recommended approach to obtain more accurate estimation of clump AGB is to measure all the DBHs of culms in a clump and then to use these DBH values in the culm biomass models.

Table 3 Models for estimating clump AGB from the number of culms per clump of 10 bamboo species.

Species	Clump biomass model	Adj. R^2 value	SEE	$P<0.05$
B. nutans	$y=45.817\,e^{0.058x}$	0.923	0.213	0.000
B. polymorpha	$y=23.892\,e^{0.065x}$	0.726	0.233	0.004
B. tulda	$y=41.016\,e^{0.040x}$	0.793	0.279	0.002
B. vulgaris	$y=7.988\,x^{0.974}$	0.877	0.203	0.000
Bambusa sp.	$y=7.852\,x^{0.948}$	0.542	0.361	0.023
C. pergracile	$y=26.591\,e^{0.041x}$	0.697	0.201	0.006
D. brandisii	$y=6.336\,x^{1.104}$	0.835	0.263	0.001
D. longispathus	$y=3.091\,x^{0.939}$	0.517	0.370	0.027
D. strictus	$y=2.065\,x^{1.148}$	0.849	0.341	0.001
T. siamensis	$y=4.551\,x^{1.050}$	0.904	0.172	0.000

Remarks: y=AGB of a clump (kg $clump^{-1}$), x=Number of culms per clump.

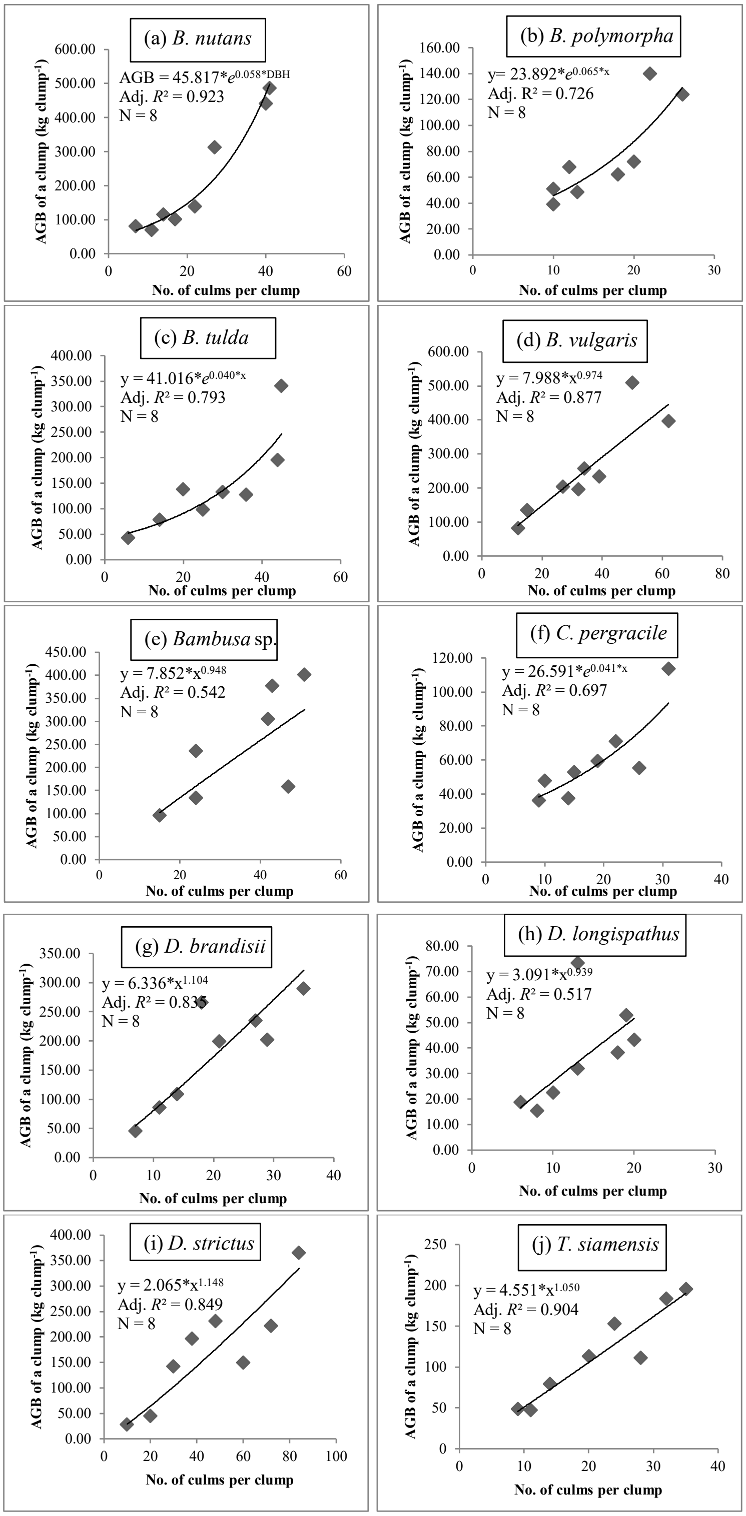

Figure 2 Relationship between number of culms per clump and AGB of clumps of (a) *B. nutans*, (b) *B. polymorpha*, (c) *B.tulda*, (d) *B. vulgaris*, (e) *Bambusa* sp., (f) *C. pergracile*, (g) *D. brandisii*, (h) *D. longispathus*, (i) *D. strictus*, and (j) *T. siamensis*.

Variation in DBH, H and Number of Culms per Clump of Ten Bamboo Species

The values for culm DBH, H, and the number of culms per clump, of the 10 bamboo species, were significantly different at $F_{(9,269)}$= 36.900 and *p*=0.000, $F_{(9,269)}$=24.769 and *p*=0.000, and $F_{(9,269)}$= 8.701 and *p*=0.000, respectively, as indicated in Table 4. *D. brandisii* and *Bambusa* sp. had the highest mean DBH (5.5 cm and 4.6 cm, respectively). There was no significant difference between *Bambusa* sp. and *B. polymorpha*, *B. vulgaris*, and *B. nutans*, which had the second highest mean DBH values of 4.6 cm, 4.4 cm, and 4.3 cm, respectively. Although *Bambusa* sp. and *B. polymorpha* had the same DBH value (4.6 cm), only *Bambusa* sp. was found to be not significantly different in DBH from *T. siamensis* (3.9 cm) and *D. longispathus* (3.6 cm). This was due to the unequal sample sizes of species resulted in different values of standard error among different pairs of species and, consequently, different test criterion values among the different pairs.

D. strictus had the smallest culms with a mean DBH of 2.0 cm. Based on the high number of culms per clump of *D. strictus* (28 culms clump^{-1}) and the fact that 59% of sampled culms were in the smallest DBH class (0.1-2.0 cm), it was concluded that these culms were dense.

The height of culms was estimated using the models presented in Table 1. Among the 10 species in the study area, *B. nutans* had the highest mean H value (11.5 m), which was not significantly different from *Bambusa* sp., *B. polymorpha*, and *D. brandisii* at 10.8 m, 11.5 m, and 9.9 m, respectively. Due to a lack of proper care and management, the values of mean DBH and H of *B. polymorpha*, *C. pergracile*, and *D. longispathus* in the present study were lower than the values of the same species obtained by Hnin (2017). They reported that the mean DBH of new culms of *B. polymorpha*, *C. pergracile*, and *D. longispathus* under different clump management trials were 6.2 cm, 6.1 cm, and 5.6 cm, respectively.

The number of culms per clump of the 10 bamboo species ranged from 10 to 33 with *Bambusa* sp., *D. strictus, B. tulda*, and *B. nutans* having the highest numbers. It should be noted that the culm density varied depending on the clump management. Hnin (2017) reported a culm density for *B. polymorpha*, *C. pergracile*, and *D. longispathus* of 9,880 culms ha^{-1}, 6,916 culms ha^{-1}, and 8,892 culms ha^{-1}, respectively, in age classes of current, 2- and 3-year-old culms, respectively. The bamboo plantation in the present study lacked proper clump management resulting in lower culm densities compared to the values obtained for bamboo under clump management trials reported by Hnin (2017).

Table 4 DBH and H of culms and number of culms per clump for the 10 bamboo species.

Species	DBH (cm)	Height (m)	No. of culms per clump (culms clump^{-1})	No. of culms per hectare (culms ha^{-1})
B. nutans	4.3^{bcde} *(±0.7)*	11.5^{a} *(±1.1)*	17^{abcd} *(±14)*	8,398
B. polymorpha	4.6^{bc} *(±1.0)*	11.5^{ab} *(±1.6)*	11^{d} *(±7)*	5,434
B. tulda	3.5^{e} *(±0.6)*	9.7^{bcd} *(±0.7)*	23^{abc} *(±16)*	11,362
B. vulgaris	4.4^{bcd} *(±0.9)*	9.0^{cd} *(±1.2)*	16^{cd} *(±15)*	7,904
Bambusa sp.	4.6^{abcd} *(±0.6)*	10.8^{abc} *(±0.9)*	33^{ab} *(±14)*	16,302
C. pergracile	3.4^{e} *(±0.8)*	9.4^{cd} *(±1.7)*	10^{d} *(±7)*	4,940
D. brandisii	5.5^{a} *(±1.3)*	9.9^{abcd} *(±1.5)*	17^{bcd} *(±10)*	8,398
D. longispathus	3.6^{de} *(±0.9)*	9.3^{cd} *(±1.8)*	12^{d} *(±8)*	5,928
D. strictus	2.0^{f} *(±0.6)*	6.5^{e} (±1.1)	28^{a} *(±19)*	13,832
T. siamensis	3.9^{de} *(±0.7)*	8.9^{d} *(±1.3)*	14^{cd} *(±11)*	6,916

Remarks: Letters a, b, c, d, e, and f represent post-hoc comparison of means. Numbers followed by the same letters in a column are not statistically different (significant level<0.05) from each other according to the Bonferroni test. The numbers in brackets represent the standard deviation from the mean value.

Variation in Biomass Components of a Culm of Ten Bamboo Species

Using the allometric models presented in Table 2, the biomass of all the components (stem, branch, and leaf) was calculated (Table 5). The stem, branch and leaf biomass of a culm varied with species at $F_{(9,269)}$=21.305 and p<0.001, $F_{(9,269)}$=59.440 and p<0.001, and $F_{(9,269)}$=61.705 and p<0.001, respectively. Comparing the values of stem biomass among the 10 species, *D. brandisii*, *B. nutans*, *Bambusa* sp., and *B. vulgaris* had a significantly higher stem biomass with values of 6.32 kg culm^{-1}, 5.77 kg culm^{-1}, 5.63 kg culm^{-1}, and 4.79 kg culm^{-1}, respectively. The second highest stem biomass was investigated in *B. polymorpha* (3.59 kg culm^{-1}), and *B. tulda* (3.56 kg culm^{-1}), which was not significantly different from *Bambusa* sp., *B. vulgaris*, and *T. siamensis*. The lowest stem biomass was obtained for in *D. strictus* (1.79 kg culm^{-1}) and *D. longispathus* (1.90 kg culm^{-1}), which was not significantly different from *C. pergracile* (2.06 kg culm^{-1}) and *T. siamensis* (3.15 kg culm^{-1}). *D. brandisii* had the highest branch biomass per culm at 2.35 kg culm^{-1}. This species also had the highest leaf biomass (0.95 kg culm^{-1}), which was significantly different from the other species.

The AGB of a culm was computed by summing the three biomass components (stem, branch, and leaf). *D. brandisii*, *B. nutans*, and *Bambusa* sp. had the highest mean AGB of a culm at 9.61 kg culm^{-1}, 7.42 kg culm^{-1}, and 6.72 kg culm^{-1}, respectively. *D. brandisii* had the highest culm biomass as it had the highest biomass in all three components. Despite a lower culm DBH compared to *D. brandisii*, the stem biomass and AGB of culm of *B. nutans* were not significantly different from *D. brandisii*. The second highest AGB of culm was obtained for *B. vulgaris* (6.56 kg culm^{-1}), which was not significantly different from *B. nutans*, *Bambusa* sp., and *B. tulda.*

Among the 10 species, *D. strictus* (2.49 kg culm^{-1}) had the lowest AGB of a culm, which was not significantly different from *C. pergracile* (2.78 kg culm^{-1}), *D. longispathus* (2.84 kg culm^{-1}), and *T. siamensis* (4.00 kg culm^{-1}). Although the culms of *D. strictus* had a significantly lower mean DBH than those of *C. pergracile*, *D. longispathus*, and *T. siamensis*, the AGB of a culm of *D. strictus* was still not significantly different due to a lack of significant difference in either the stem or the branch biomass.

Table 5 Mean stem, branch, leaf, and AGB of the ten bamboo species.

Species	Biomass (kg culm^{-1})			
	Leaf	Branch	Stem	Total
B. nutans	0.29^{cde} *(±0.08)*	1.35^{b} *(±0.53)*	5.77^{a} *(±2.40)*	7.42^{ab} *(±3.01)*
B. polymorpha	0.26^{de} *(±0.10)*	0.47^{d} *(±0.15)*	3.59^{bc} *(±1.97)*	4.32^{cdef} *(±2.22)*
B. tulda	0.22^{de} *(±0.11)*	1.03^{bc} *(±0.38)*	3.56^{bcd} *(±1.48)*	4.81^{bcde} *(±1.97)*
B. vulgaris	0.56^{b} *(±0.14)*	1.21^{bc} *(±0.33)*	4.79^{ab} *(±1.99)*	6.56^{b} *(±2.46)*
Bambusa sp.	0.37^{cde} *(±0.12)*	0.72^{cd} *(±0.22)*	5.63^{ab} *(±1.64)*	6.72^{abcd} *(±1.99)*
C. pergracile	0.29^{de} *(±0.08)*	0.43^{d} *(±0.12)*	2.06^{de} *(±0.94)*	2.78^{fg} *(±1.33)*
D. brandisii	0.95^{a} *(±0.32)*	2.35^{a} *(±1.06)*	6.32^{a} *(±3.62)*	9.61^{a} *(±4.99)*
D. longispathus	0.43^{c} *(±0.16)*	0.51^{d} *(±0.25)*	1.90^{e} *(±0.94)*	2.84^{efg} *(±1.34)*
D. strictus	0.20^{e} *(±0.12)*	0.51^{d} *(±0.27)*	1.79^{e} *(±1.16)*	2.49^{g} *(±1.55)*
T. siamensis	0.33^{cd} *(±0.12)*	0.52^{d} *(±0.24)*	3.15^{cde} *(±1.31)*	4.00^{defg} *(±1.67)*

Remarks: Letters a, b, c, d, e, f, and g represent post-hoc comparison of means. Numbers followed by the same letters in a column are not statistically different (significant level<0.05) from each other according to Bonferroni test. The numbers in brackets represent the standard deviation from the mean value.

Variation in AGB of Clumps of the Ten Bamboo Species

The AGB of clumps of the ten bamboo species was computed by summing the AGB of culms in a clump. The AGB of clumps significantly varied between species ($F_{(9,269)}$=9.617 and p<0.001), as presented in Table 6. *Bambusa* sp. had the highest AGB per clump (223.93 kg clump^{-1}), which was not significantly different from *D. brandisii* (161.38 kg clump^{-1}), *B. nutans* (149.58 kg clump^{-1}), and *B. tulda* (121.14 kg clump^{-1}). The high AGB of culms and number of culms per clump in these species contributed to the highest AGB of clumps. Similarly, *C. pergracile* and *D. longispathus* with the lowest culm AGB and number of culms per clump had the lowest AGB of clumps values which were not significantly different from the values for *B. polymorpha* (50.45 kg clump^{-1}), *T. siamensis* (66.80 kg clump^{-1}), and *D. strictus* (81.84 kg clump^{-1}). Among these species, the culm density of *D. strictus* was significantly higher. However, there being no significant differences in the AGB of a culm of species *C. pergracile*, *D. longispathus,* and *T. siamensis,* contributed to the non-significant difference in the AGB of clumps among these species. This result was in agreement with Nath *et al*. (2015), who reported a weak correlation between the culm stand density and biomass of the stock (R^2=0.14). It can be assumed that the contribution to the clump AGB was both by the number of culms per clump and the DBH of the culms. Thus, to obtain a high AGB of clumps, it is recommended to adopt clump management with an optimal number of culms per clump which produces culms with a high DBH.

As observed during the data collection of the present study, bamboos in the study area seemingly lacked proper care and maintenance. The presence of clumps, congested with broken and dead culms, also indicated that clump management had not been conducted in the area. Lack of management and repeated shoot harvesting by villagers likely can be attributed to a low AGB. Virtucio and Roxas (2003) indicated that poor management practices in a plantation may contribute to a reduced production of culms and shoots. Hnin (2017) also indicated that different clump management trials resulted in different values of AGB.

Plantation AGB

The AGB of each bamboo species per hectare was computed by multiplying the number of clumps per hectare (494 clumps ha^{-1}) by the mean AGB per clump of each species. These values are presented in Table 6. The AGB of *B. vulgaris* (54.69 t ha^{-1}) in the present study was lower than the value of 72.20 t ha^{-1} reported by Patricio and Dumago (2014) and of 121.50 t ha^{-1} reported by Nath *et al*. (2009). Maintaining a culm age structure of 3:3:2:1:1 for the current, 1-, 2-,3-, and 4-year-old culms in the stand could probably have contributed to the higher mean DBH and H values (14.5 cm and 7.4 m, respectively) and consequently, a higher mean AGB of the *B. vulgaris* stand in North East India (Nath *et al*., 2009).

The AGB of *B. nutans* (73.89 t ha^{-1}) and *D. brandisii* (79.72 t ha^{-1}) in the present study was comparable with the value of 74.70 t ha^{-1} for *D. strictus* recorded in a 5-year-old plantation in the Singrauli coalfield in India (Singh and Singh, 1999). The AGB of 40.71 t ha^{-1} of *D. strictus* in the present study was comparable with that of 46.00 t ha^{-1} for 3-year-old *D. strictus* plantation in the Singrauli coalfield (Singh and Singh, 1999). Lack of plantation care and management in the present study area might account for the AGB value being comparable with the reported value of a young plantation in the dry tropical region, although the clumps in this study had a well-established rhizome system.

The AGB values of *B. polymorpha*, *C. pergracile*, and *D. longispathus* obtained in the present study were comparably lower than the values of 42.65 t ha^{-1} for *B. polymorpha*, 21.54 t ha^{-1} for *C. pergracile*, and 26.46 t ha^{-1} for *D. longispathus*, which were subjected to the different clump management trials, reported by Hnin (2017). Clump management and seasonal prohibition of shoot harvest by nearby villager are highly recommended in the study area.

Using the number of clumps of each bamboo species sampled and the mean AGB of clumps of each species, the total AGB of a 14-year-old plantation with an area of 19 ha at Moeswe was estimated to be around 773.40 t, to which the contribution from *D. brandisii* was the highest (130.30 t, 16.85%), followed by *B. vulgaris* (115.11 t, 14.88%), *D. strictus* (99.12 t, 12.82%), *B. tulda* (97.81 t, 12.65%), *B. polymorpha* (67.89 t, 8.78%), *T. siamensis* (65.17 t, 8.43%), *B. nutans* (60.39 t, 7.81%), *Bambusa* sp. (60.27 t ha^{-1}, 7.79%), *C. pergracile* (40.67 t, 5.26%), and *D. longispathus* (36.68 t, 4.74%). The biomass estimated in this study can be converted to carbon estimates using the known conversion factor (0.47) and the aboveground carbon storage of the plantation can be estimated (Egglest *et al*., 2006; Leksungnoen, 2017).

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CONCLUSION

This study was conducted in order to provide the information on the growth of bamboo in terms of AGB to an interested farmer and community user group and to encourage them to raise bamboo for a continuous bamboo supply. The DBH of a culm was found to be the best-fit predictor variable to estimate the biomass of a culm. The predictive models developed in the present study could be useful in estimating the aboveground biomass of plantations or natural stands on sites with similar climatic, edaphic, and human disturbance conditions. However, validation of the models is recommended before any practical application is undertaken. The mean AGB of clumps of the 10 species was in the order of *Bambusa* sp.>*D. brandisii*> *B. nutans*>*B. tulda*> *B. vulgaris*> *D. strictus*> *T. siamensis*> *B. polymorpha* > *D. longispathus*> *C. pergracile*, providing growth information of these species to forestry professionals, potential bamboo growers, and community forestry user groups. The adoption of a clump management is recommended to obtain higher biomass in all bamboo species in the plantation.

Different species have different rates of biomass accumulation in the leaf, branch, and stem components of a culm, and number of culms per clump and consequently, in the AGB of clumps. For a complete picture of how the stem biomass accumulates, a study on the relationship between culm wall thickness and stem biomass of different bamboo species is necessary. It is also an urgent need to study the taxonomy of *Bambusa* sp., since it displayed

Table 6 Estimated AGB of the 14 years old, 19 ha bamboo plantation at the Moeswe Research Station, Myanmar

Species	Number of clumps sampled	Number of clumps contributing to one hectare	Estimated number of clumps in 19 ha plantation	Mean AGB per clump (kg clump^{-1})	AGB per hectare (t ha^{-1})	AGB contributed to one hectare (t)	Estimated AGB in 19 ha plantation (t)	Percent contribution to the total AGB of 19 ha plantation (%)
B. nutans	12	21	404	149.58^{abc}	73.89	3.18	60.39	7.80
B. polymorpha	40	71	1,346	50.45^{de}	23.05	3.57	67.89	8.78
B. tulda	24	42	807	121.14^{abcd}	59.10	5.15	97.81	12.65
B. vulgaris	32	57	1,077	106.93^{bcd}	54.69	6.06	115.11	14.88
Bambusa sp.	8	14	269	223.93^{a}	109.38	3.17	60.27	7.79
C. pergracile	42	74	1,413	28.78^{e}	14.22	2.14	40.67	5.26
D. brandisii	24	42	807	161.38^{ab}	79.72	6.86	130.30	16.85
D. longispathus	32	57	1,077	34.08^{e}	16.66	1.93	36.68	4.74
D. strictus	36	64	1,211	81.84^{cde}	40.71	5.22	99.12	12.82
T. siamensis	29	51	976	66.80^{cde}	31.90	3.43	65.17	8.43
Total	**279**	**494**	**9,386**			**40.71**	**773.40**	**100.00**

Remarks: Letters a, b, c, d, and e represent post-hoc comparison of means. Numbers followed by the same letters in a column are not statistically different (significant level<0.05) from each other according to the Bonferroni test.

the highest AGB among the 10 bamboo species. Studies focusing on the relationship between the culm wall thickness and stem biomass are recommended for greater understanding of stem biomass accumulation. The age of culms should also be considered when selecting culms for destructive sampling.

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