

Site- and species-specific allometric equations for culm biomass estimation of four tropical bamboo species on Lombok Island, Indonesia

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Abstract

Bamboo is a rapidly renewable resource with considerable potential for biomass production and carbon sequestration. Therefore, site species-specific allometric models are necessary for reliable biomass estimation in individual species. This study aimed to develop and evaluate site species-specific allometric equations for estimating the culm biomass of four dominant tropical bamboo species (*Bambusa vulgaris* Schrad. ex J.C.Wendl., *Dendrocalamus asper* (Schult. & Schult.f.) Backer, *Gigantochloa apus* (Schult.f.) Kurz ex Munro, and *Gigantochloa atter* (Hassk.) Kurz ex Munro) on Lombok Island, Indonesia. Field data were obtained through an inventory of bamboo culms followed by destructive sampling based on diameter class. Culm diameter, culm height, and number of internodes were assessed as predictor variables using power-function models. Model performance was evaluated using the coefficient of determination (R^2), the Akaike Information Criterion (AIC), and the root mean square error (RMSE). Diameter was the most consistent predictor across the four species, while culm height and number of internodes contributed differently among species. The selected allometric models were species-specific: *B. vulgaris* ($Y = 0.036 \cdot D^{1.548} \cdot H^{0.961}$), *D. asper* ($Y = 0.107 \cdot D^{2.162}$), *G. apus* ($Y = 0.021 \cdot D^{1.261} \cdot H^{1.254}$) and *G. atter* ($Y = 0.476 \cdot D^{2.705} \cdot R^{-0.792}$). The developed equations provide a practical and non-destructive method for estimating biomass at the individual culm level. When combined with data on stand density, diameter distribution, and carbon fractions, these equations can support further research on biomass and carbon stock estimates per hectare.

Key words: bamboo allometry, *Bambusa vulgaris*, *Dendrocalamus asper*, *Gigantochloa apus*, *Gigantochloa atter*

Introduction

Bamboo is characterised by rapid growth, with maximum daily height increments of approximately 33–37 cm reported for

some species, although growth rates vary among species and growth conditions (Decipulo et al. 2009, Nath and Das 2012). Globally, bamboo is recognised as a renewable biomass resource that can

store significant amounts of carbon. At the ecosystem level, the total carbon stocks of bamboo ecosystems are comparable to those reported for rubber plantations and tree orchards, although they are generally lower than those of most forest types (Yuen et al. 2017). In addition, bamboo has long been utilised by local communities for construction, handicrafts, food, and energy, while also providing an important source of household income (Prayogo et al. 2021). Thus, bamboo has substantial ecological, economic, and social value.

In the context of climate change mitigation, bamboo is considered strategic due to its ability to rapidly sequester carbon through the accumulation of aboveground and belowground biomass (Prayogo et al. 2021, Singnar et al. 2021). Despite its considerable potential for carbon storage, accurate estimation of bamboo biomass remains challenging because biomass estimates are strongly influenced by species characteristics, stand conditions, and selection of allometric model. Generic models developed for trees or bamboo in other locations often fail to capture the morphological variation among species or local ecological conditions. Therefore, species-specific allometric equations are required to obtain reliable biomass and carbon estimates (Kaam et al. 2023, García et al. 2024).

Studies from various countries demonstrate that diameter at breast height is generally the most critical predictor of bamboo biomass. However, the total height, number of internodes, and culm age also contribute significantly (Kaam et al. 2023, Yen et al. 2023). For instance, research on *Bambusa vulgaris* Schrad. ex J.C.Wendl. in Cameroon revealed that the best models combined DBH, culm height, and age (Kaam et al. 2023), while for *Guadua angustifolia* Kunth in Colombia,

simple DBH-based models were found to be the most practical for carbon inventory purposes (García et al. 2024). Other studies in Ethiopia also highlight the importance of site-specific approaches, showing that carbon stocks of *Oldeania alpina* (K. Schum.) Stapleton varied significantly between natural forests and homestead stands (Yebeyen et al. 2022, Burru et al. 2025).

Beyond species and site variation, biomass allocation across plant components also plays a critical role. In *Bambusa vulgaris* var. *striata* (Lodd. ex Lindl.) Gamble in Indonesia, the culm contributed the highest proportion of biomass (48 %), followed by branches (28 %) and leaves (24 %) (Mulyana et al. 2025). Similarly, studies on *Dendrocalamus latiflorus* Munro in Taiwan reported that culms accounted for more than 65 % of total biomass (Yen et al. 2023). These findings emphasise that the morphological structure of each species directly influences biomass distribution and carbon content. Many existing allometric models have been developed for a limited number of species or under specific ecological conditions, which may reduce their transferability and increase uncertainty when applied beyond their original context. Furthermore, empirical data relating allometric biomass estimates to carbon storage in bamboo culms remain limited, particularly for tropical clumping bamboos in Southeast Asia.

Indonesia hosts high diversity of bamboo species that are widely distributed in community forests and agroforestry systems. On Lombok Island, species such as *Bambusa vulgaris*, *Dendrocalamus asper* (Schult. & Schult.f.) Backer, *Gigantochloa apus* (Schult.f.) Kurz ex Munro, and *Gigantochloa atter* (Hassk.) Kurz ex Munro are among the most dominant and economically important bamboos. Despite

their extensive use and ecological relevance, quantitative information on species-specific allometric relationships and biomass accumulation for these bamboos remains scarce. In addition, climatic conditions across bamboo-growing areas, including variations in rainfall, temperature, and seasonality, may influence bamboo growth patterns and biomass accumulation. This knowledge gap constrains the integration of bamboo into national carbon inventories and limits its recognition in climate mitigation strategies. Therefore, this study aims to examine species-specific allometric relationships between culm morphological variables and culm biomass for four dominant bamboo species on Lombok Island. The resulting equations may contribute to improved biomass estimation and carbon accounting for tropical

bamboo ecosystems.

Materials and Methods

Study site

This study was conducted on Lombok Island, West Nusa Tenggara Province, Indonesia. Three representative study sites were selected: Aik Bual Community Forest, Kabul Village, and Keruak Village (Fig. 1). These sites were chosen to represent the dominant bamboo species occurring in the study area. All sample plots were located in community-owned forests, where bamboo grows naturally without active management or silvicultural intervention. *B. vulgaris* and *G. atter* were sampled in Kabul and Keruak villages,

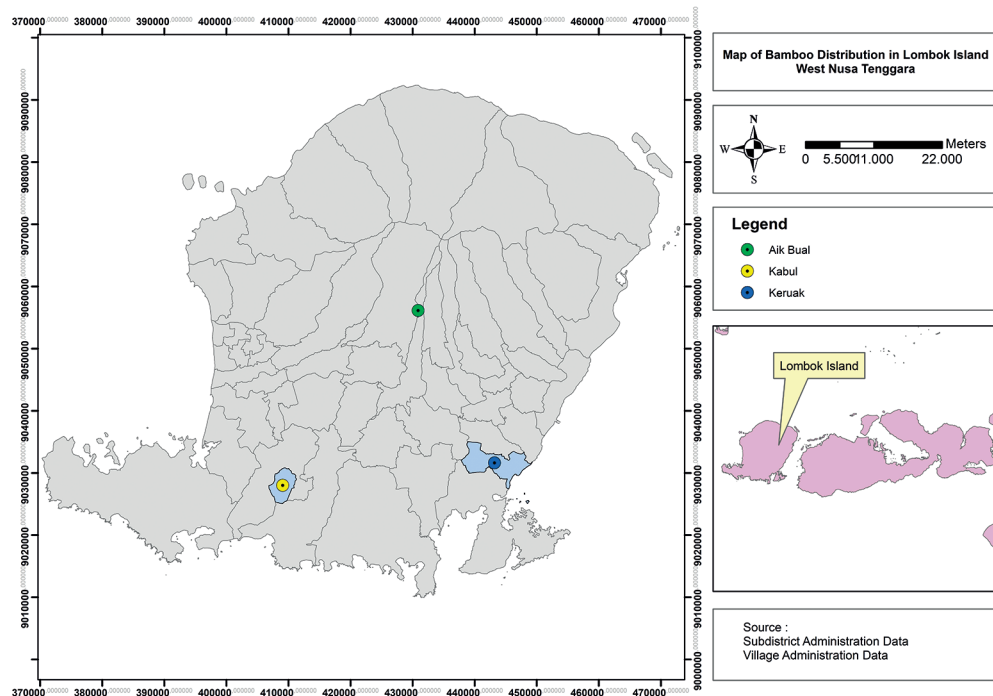


Fig. 1. Location map of the study sites.

Note: The map was created using ArcGIS (version 10.8) software.

whereas *D. asper* and *G. apus* were sampled in Aik Bual Community Forest. The three study sites differed in their environ-

mental characteristics (Rini et al. 2023, FAO 2026). Further details of the study sites are provided in Table 1.

Table 1. Details of study sites.

Site	Location	Coordinates	Elevation, m a.s.l	Mean annual temp, °C	Annual precipitation, mm	Soil type
I	Aik Bual, Central Lombok	116°22'19.465" E, 8°32'18.252" S	500	26.5	2049	Andosol
II	Kabul Village, Central Lombok	116°10'24.227" E, 8°47'32.599" S	641	23.5	1821	Inceptisol
III	Keruak Village, East Lombok	116°29'1.337" E, 8°45'36.959" S	37	26.9	705	Inceptisol

Note: Soil types were obtained from the FAO soil map (2026), while mean annual temperature and annual precipitation data were obtained from Rini et al. (2023).

Bamboo stand inventory

A complete census approach was used to inventory bamboo stands at each study site because the number of clumps was relatively limited. For each species, the number of clumps, number of culms per clump, and diameter of each culm within each clump were recorded. Culm diameter was measured at 1.3 m above ground level, following standard bamboo inventory practices (Mulyana et al. 2025). The inventory data were used to characterise stand structure and to inform the selection of representative culms for destructive sampling.

Diameter class stratification

Due to the difficulty and uncertainty associated with determining culm age in the field, particularly in unmanaged, community-owned bamboo stands, culms were classified into three diameter classes (small, medium, and large). This approach was adopted because direct determination of culm age is difficult, whereas culm diameter provides a practical basis

for capturing the size structure of bamboo populations (García et al. 2024, Liu and Yen 2025, Mulyana et al. 2025). Diameter class limits varied among species to account for interspecific differences in culm size. This stratification ensured adequate representation of all major size classes contributing to culm biomass (García et al. 2024). However, culm diameter may also be influenced by species characteristics, clump vigour, site conditions, and management history. Therefore, diameter classes were used primarily for sampling stratification and were not interpreted as indicators of culm age.

Morphological measurements

For each diameter class and species, representative culms were selected for detailed morphological measurements. Culm diameter (cm), culm height (m), number of internodes, and total green culm biomass were recorded. Culm diameter was measured at 1.3 m above ground level. Culm height was measured after felling from the cut base to the tip, with the height of the remaining stump added to obtain the to-

tal culm height. The number of internodes was determined by direct counting along the entire culm. These variables were selected for their biological relevance and their frequent use as potential predictors in bamboo allometric models for biomass estimation (Kaam et al. 2023, Yen et al. 2023, García et al. 2024).

Destructive sampling and biomass determination

Destructive sampling was conducted on selected culms within each diameter class for each species. Only the culm component was considered in this study. Selected culms were cut at ground level and separated into components as required (Niklas and Enquist 2002). The green weight of each culm was measured, and the culm material was subsequently dried at 105°C until a constant weight. The resulting dry weight was recorded as the dry biomass. Culm biomass was expressed on a per-culm basis ($\text{kg} \cdot \text{culm}^{-1}$).

Statistical analysis

All statistical analyses and modelling were carried out using *R* software (*R* Core Team 2025). Descriptive statistics were used to summarise stand structure, culm characteristics, and culm biomass. Differences in biomass among diameter classes and species were interpreted in terms of culm morphology and growth characteristics. Species-specific allometric models were developed to estimate dry culm biomass using morphological variables, namely culm diameter (D), culm height (H), and number of internodes (R). Power-function models were fitted in the following general form (1):

$$Y = a \cdot D^b \cdot R^c \cdot H^d, \quad (1)$$

where: Y is the culm dry biomass, kg; D is

the culm diameter at 1.3 m height, cm; R is the number of internodes; H is the culm length, m; a is the scaling coefficient; b , c , and d are species-specific allometric exponents.

To estimate the parameters of the model using ordinary least squares (OLS) regression, all variables were transformed using natural logarithms. The linearised form of the model is given in Equation (2):

$$\ln(Y) = \ln(a) + b \ln(D) + c \ln(R) + d \ln(H). \quad (2)$$

A total of seven candidate models, comprising single- and multiple-predictor models, were evaluated for each species. OLS regression was performed using the stats package, while broom (Robinson et al. 2025) and Metrics (Hamner et al. 2018) packages were used to summarise model outputs and evaluate predictive performance, respectively. The best model for each species was selected based on a combined assessment of the coefficient of determination (R^2), Akaike Information Criterion (AIC), root mean square error (RMSE), model parsimony, and biological interpretability (Burnham and Anderson 2002). The predictions on the logarithmic scale were then back-transformed to the original scale.

To reduce retransformation bias when converting predictions from the logarithmic scale to the original biomass scale, a correction factor (CF) based on the model residual variance was applied following Picard et al. (2012). Model assumptions were assessed by examining residuals-versus-fitted plots to identify heteroscedasticity and systematic residual patterns (Zuur et al. 2009). The visual assessment was complemented by a studentised Breusch–Pagan test using the bptest function in the lmtest package (Breusch and Pagan 1979, Zeileis and Hothorn 2002). Leave-one-out cross-val-

idation (LOOCV) was applied to the final model selected for each bamboo species to evaluate its predictive performance through internal validation.

Results and Discussion

Stand structure and diameter class distribution

The stand characteristics of each bamboo species at the selected study sites are presented in Table 2, including the number of clumps, number of culms per clump, and culm diameter. Variation in culm diameter within a clump reflects differences in clump structure rather than the age of individual culms. The size and vigour of emerging shoots influence the eventual diameter of newly developed culms. This

variation may be influenced by the physiological vigour of the clump, particularly the number and condition of mother culms. Their nutrient and starch reserves support the development and growth of emerging shoots (Bahru and Ding 2020). In general, older bamboo clumps tend to produce smaller shoots and culms with smaller diameters (García and Kleinn 2010). However, accurately determining culm age in the field is difficult, as age identification often relies on external morphological indicators and specialised techniques and is therefore prone to error (Liese and Weiner 1996, Xu et al. 2022). In addition, bamboo culms attain their maximum height within few weeks to several months, after which they undergo no secondary diameter growth. Subsequent development primarily involves lignification and tissue maturation (Liese and Köhl 2015).

Table 2. Number of clumps and mean ($\pm$ SD) values for culms per clump and culm diameter.

Species	Site	Number of clumps	Culms per clump		Culm diameter, cm	
			Mean	SD	Mean	SD
<i>Bambusa vulgaris</i>	II	33	58	26.6	6.8	1.2
	III	24	63	36.5	6.0	2.0
<i>Dendrocalamus asper</i>	I	21	17	11.4	9.2	3.0
<i>Gigantochloa apus</i>	I	70	30	16.1	6.6	2.2
<i>Gigantochloa atter</i>	II	35	48	29.7	7.8	1.7
	III	52	74	38.8	6.2	1.8

Note: SD – standard deviation.

Therefore, to represent the overall size structure of bamboo population, culms were classified into three diameter classes: small, medium, and large. The diameter class approach is commonly used to characterise bamboo stand structure, as diameter distribution is an essential characteristic of stand structure (García and Kleinn 2010, Liu and Yen 2025). The di-

ameter classes for each species are presented in Table 3.

Table 3 shows that diameter-class limits varied among species, reflecting interspecific differences in culm size. Culm diameter ranged from 1.6 to 11.7 cm in *B. vulgaris*, 1.9 to 16.2 cm in *D. asper*, 1.3 to 10.8 cm in *G. apus*, and 1.6 to 12.9 cm in *G. atter*. Among studied species, *D. asper*

Table 3. Bamboo diameter classes based on species.

Species	Diameter classes, cm
<i>Bambusa vulgaris</i>	1.6 – 4.9
	5.0 – 8.3
	8.4 – 11.7
<i>Dendrocalamus asper</i>	1.9 – 6.6
	6.7 – 11.4
	11.5 – 16.2
<i>Gigantochloa apus</i>	1.3 – 4.4
	4.5 – 7.6
	7.7 – 10.8
<i>Gigantochloa atter</i>	1.6 – 5.3
	5.4 – 9.1
	9.2 – 12.9

had larger diameters, consistent with findings from previous studies (Damayanto et al. 2020, Perumal et al. 2023, Rini et al. 2023, Zeleke and Ararso 2023).

Bamboo morphology and culm biomass

Table 4 presents the mean morphological

characteristics and culm dry biomass of the four bamboo species. Overall, culm diameter, number of internodes, and dry biomass tended to increase from the small to the large diameter class. Culm height generally showed a similar pattern, although some variation occurred among species and diameter classes. These differences reflect species-specific culm morphology and biomass accumulation patterns, which may also be influenced by environmental conditions (Ogbemudia et al. 2023).

Based on Table 4, the morphology and biomass of each species are as follows: 1) *B. vulgaris* showed clear increase in biomass with increasing culm diameter. This indicates that diameter is an important predictor of culm biomass in this species. 2) *D. asper* exhibited the highest biomass among the studied species. This indicates that its large culm size was associated with high biomass accumulation. 3) *G. apus* had relatively slender culms, while its biomass increased with increas-

Table 4. Mean ($\pm$ SD) values of bamboo morphological characteristics and culm dry biomass.

Species	Diameter classes	<i>n</i>	Culm diameter, cm	Number of internodes	Culm height, m	Dry biomass, kg
<i>Bambusa vulgaris</i>	Small	10	2.8 $\pm$ 0.6	29.0 $\pm$ 6.8	7.8 $\pm$ 2.1	1.4 $\pm$ 1.2
	Medium	10	6.2 $\pm$ 0.5	51.0 $\pm$ 10.2	13.8 $\pm$ 3.0	9.0 $\pm$ 3.5
	Large	10	9.2 $\pm$ 0.3	53.0 $\pm$ 10.8	17.6 $\pm$ 3.2	14.2 $\pm$ 2.7
<i>Dendrocalamus asper</i>	Small	5	5.1 $\pm$ 0.6	38.0 $\pm$ 8.8	12.2 $\pm$ 3.0	3.4 $\pm$ 1.8
	Medium	5	9.5 $\pm$ 0.6	49.0 $\pm$ 11.0	19.6 $\pm$ 5.1	15.1 $\pm$ 6.7
	Large	5	13.2 $\pm$ 0.5	59.0 $\pm$ 22.0	18.1 $\pm$ 6.1	25.9 $\pm$ 11.2
<i>Gigantochloa apus</i>	Small	5	3.2 $\pm$ 0.3	17.6 $\pm$ 3.6	8.1 $\pm$ 1.6	1.3 $\pm$ 0.5
	Medium	5	6.3 $\pm$ 0.3	38.4 $\pm$ 11.6	14.4 $\pm$ 3.3	6.2 $\pm$ 2.4
	Large	5	9.0 $\pm$ 0.5	47.8 $\pm$ 6.5	17.4 $\pm$ 3.4	11.7 $\pm$ 5.2
<i>Gigantochloa atter</i>	Small	10	3.9 $\pm$ 0.4	29.9 $\pm$ 5.7	8.9 $\pm$ 3.7	1.2 $\pm$ 0.3
	Medium	10	6.8 $\pm$ 1.1	40.5 $\pm$ 4.8	12.2 $\pm$ 1.8	4.8 $\pm$ 1.3
	Large	10	10.5 $\pm$ 0.5	47.7 $\pm$ 9.3	14.0 $\pm$ 4.7	13.8 $\pm$ 4.1

Note: *n* – number of culms. Culm diameter was measured at 1.3 m above ground level. Culm height was measured from base to tip after felling.

ing culm diameter. Its smaller culm dimensions are consistent with its common use for weaving, handicrafts, and light construction. 4) *G. atter* exhibited intermediate culm dimensions among studied species. Its biomass increased with culm diameter and length, indicating moderate biomass accumulation pattern in this species.

These results are consistent with previous studies showing that larger culm diameter is associated with greater biomass accumulation (Kaushal et al. 2022, Adu-Poku et al. 2023). The relatively high biomass of *D. asper*, observed in this study, may be associated with its large culm diameter. Sutyono et al. (2022) reported that *D. asper* attained a biomass of $108 \text{ kg} \cdot \text{m}^{-1}$ of clump circumference, indicating its considerable potential for biomass production. In contrast, *G. apus* had shorter culms and fewer internodes than *D. asper* (Zelege and Ararso 2023), reflecting interspecific differences in culm morphology, rather than differences in growth rate. In addition, the diverse uses of *G. atter* indicate its potential as a renewable resource for sustainable production when supported by appropriate cultivation and harvesting practices (Dransfield and Widjaja 1995, Paembonan 2019, Pujiarti et al. 2022).

Allometric model performance

The biomass and predictor variables were transformed into natural logarithms, and the parameters of seven candidate models were estimated using ordinary least squares (OLS) regression. The estimated intercepts and regression coefficients were subsequently back-transformed to obtain power-function equations on the original biomass scale, with a correction factor (CF) applied to mitigate retransformation bias. The candidate models were

evaluated and compared using Akaike's Information Criterion (AIC), the coefficient of determination (R^2), and root mean square error (RMSE), as summarised in Table 5.

Culm diameter (D) emerged as the primary predictor explaining biomass variation across all evaluated species. This aligns with findings by Chantararat et al. (2023), who demonstrated that allometric models grounded in culm diameter accurately predict biomass productivity in tropical bamboos. Nevertheless, model performance reflected species-specific morphological traits. The contribution of additional predictors varied among species. The number of internodes contributed to the selected model for *G. atter*, whereas culm height was retained for *B. vulgaris* and *G. apus*. In *D. asper*, the $D+H$ model showed the best overall statistical performance. However, the difference in AIC between the $D+H$ and diameter-only models was small ($\Delta\text{AIC} = 0.7$). Therefore, the diameter-only model was selected because of its greater parsimony and practical applicability for field-based biomass estimation. Parameter estimates and standard errors for the selected models are detailed in Table 6.

Based on the parameter estimates of the selected allometric models, culm diameter was the most consistent predictor of culm dry biomass across all species. This was indicated by the positive and significant diameter coefficient (b) obtained for each species. These results indicate that dry biomass increases with increasing culm diameter. Biologically, culm diameter reflects culm size and structural development. Therefore, larger culm diameters are generally associated with greater tissue volume and biomass.

In *B. vulgaris* and *G. apus*, both culm diameter and culm height had positive

Table 5. Comparison of allometric equation models with culm diameter, culm height, and number of internodes as the predictor variables.

Species	<i>n</i>	Model	AIC	R ²	RMSE
<i>Bambusa vulgaris</i>	30	<i>D+R+H</i>	32	0.722	3.06
		<i>D+R</i>	32.6	0.803	2.58
		<i>D+H</i>	30	0.716	3.10
		<i>R+H</i>	54.7	0.456	4.29
		<i>D</i>	36.4	0.690	3.24
		<i>R</i>	70.5	0.424	4.41
		<i>H</i>	53.2	0.511	4.07
<i>Dendrocalamus asper</i>	15	<i>D+R+H</i>	22.6	0.814	4.94
		<i>D+R</i>	22.7	0.764	5.56
		<i>D+H</i>	20.9	0.831	4.71
		<i>R+H</i>	38.3	0.461	8.40
		<i>D</i>	21.6	0.662	6.66
		<i>R</i>	38.9	0.497	8.12
		<i>H</i>	36.4	0.397	8.89
<i>Gigantochloa apus</i>	15	<i>D+R+H</i>	11.7	0.913	1.53
		<i>D+R</i>	18.4	0.814	2.25
		<i>D+H</i>	10.1	0.911	1.55
		<i>R+H</i>	19.2	0.790	2.38
		<i>D</i>	16.9	0.799	2.34
		<i>R</i>	27.3	0.608	3.26
		<i>H</i>	18.8	0.806	2.29
<i>Gigantochloa atter</i>	30	<i>D+R+H</i>	24	0.821	2.46
		<i>D+R</i>	22.1	0.823	2.45
		<i>D+H</i>	26.7	0.817	2.49
		<i>R+H</i>	77.4	0.310	4.82
		<i>D</i>	24.7	0.817	2.49
		<i>R</i>	75.4	0.317	4.80
		<i>H</i>	92.7	0.172	5.76

Note: *n* – number of culms; *D* – culm diameter at 1.3 m height; *H* – culm height; *R* – number of internodes. Model combinations indicate the predictor variables included in each allometric model (e.g. *D+H* – culm diameter and culm height; *D+R* – culm diameter and number of internodes; *D+R+H* – culm diameter, number of internodes, and culm height). Bold values indicate the minimum AIC and RMSE, and the highest R² among seven models.

Table 6. Parameter estimates and standard errors of selected models.

Species	Model	CF	Parameter	Estimate	SE	p-value
<i>Bambusa vulgaris</i>	<i>D+H</i>	1.08	<i>a</i>	0.036	0.018	<0.001
			<i>b</i>	1.548	0.259	<0.001
			<i>d</i>	0.961	0.325	0.006
<i>Dendrocalamus asper</i>	<i>D</i>	1.09	<i>a</i>	0.107	0.066	0.002
			<i>b</i>	2.162	0.282	<0.001
<i>Gigantochloa apus</i>	<i>D+H</i>	1.04	<i>a</i>	0.021	0.012	<0.001
			<i>b</i>	1.261	0.356	0.004
			<i>d</i>	1.254	0.403	0.009
<i>Gigantochloa atter</i>	<i>D+R</i>	1.05	<i>a</i>	0.476	0.504	0.459
			<i>b</i>	2.705	0.226	<0.001
			<i>c</i>	-0.792	0.372	0.043

Note: *n* – number of culms; *D* – culm diameter at 1.3 m height; *H* – culm height; *R* – number of internodes. Model combinations indicate the predictor variables included in each allometric model (e.g. *D+H* = diameter and height; *D+R* = diameter and number of internodes). CF – transformation correction factor; *a*, *b*, *c*, *d* – allometric equation coefficients; SE – standard error; *p*-value – indicate the statistical significance of the estimated model parameters.

and significant coefficients. This indicates that biomass variation in these species was associated not only with culm diameter but also with culm height. Thus, the combination of culm diameter and height provided better representation of biomass variation in these species. In *G. atter*, the selected model included culm diameter and number of internodes (*D+R*). Culm diameter had a positive and significant coefficient, whereas the number of internodes had a negative and significant coefficient. This negative coefficient should be interpreted with caution, as it does not necessarily indicate that an increase in the number of internodes directly reduces biomass. After accounting for culm diameter, the negative coefficient may reflect species-specific morphological variation, although it may also be influenced by correlations among predictors and the limited sample size. Therefore, this relationship should not be interpreted as evidence of

a direct biological trade-off.

The agreement between the observed and fitted biomass values was visually evaluated using scatter plots with a 1:1 reference line (Fig. 2). The plots showed generally good agreement between the observed and model-predicted biomass values across all four bamboo species. The adequacy of the selected models was further assessed using residuals-versus-fitted plots on the log-transformed scale (Fig. 3). The residuals were distributed around zero and showed no pronounced funnel-shaped pattern, indicating no clear evidence of heteroscedasticity. In addition, the studentised Breusch–Pagan test yielded *p*-values > 0.05 for all species. Although some individual observations showed relatively large residuals, the overall residual distribution suggested that the assumption of homoscedasticity was reasonably satisfied. Together with the AIC, *R*², RMSE, and biological inter-

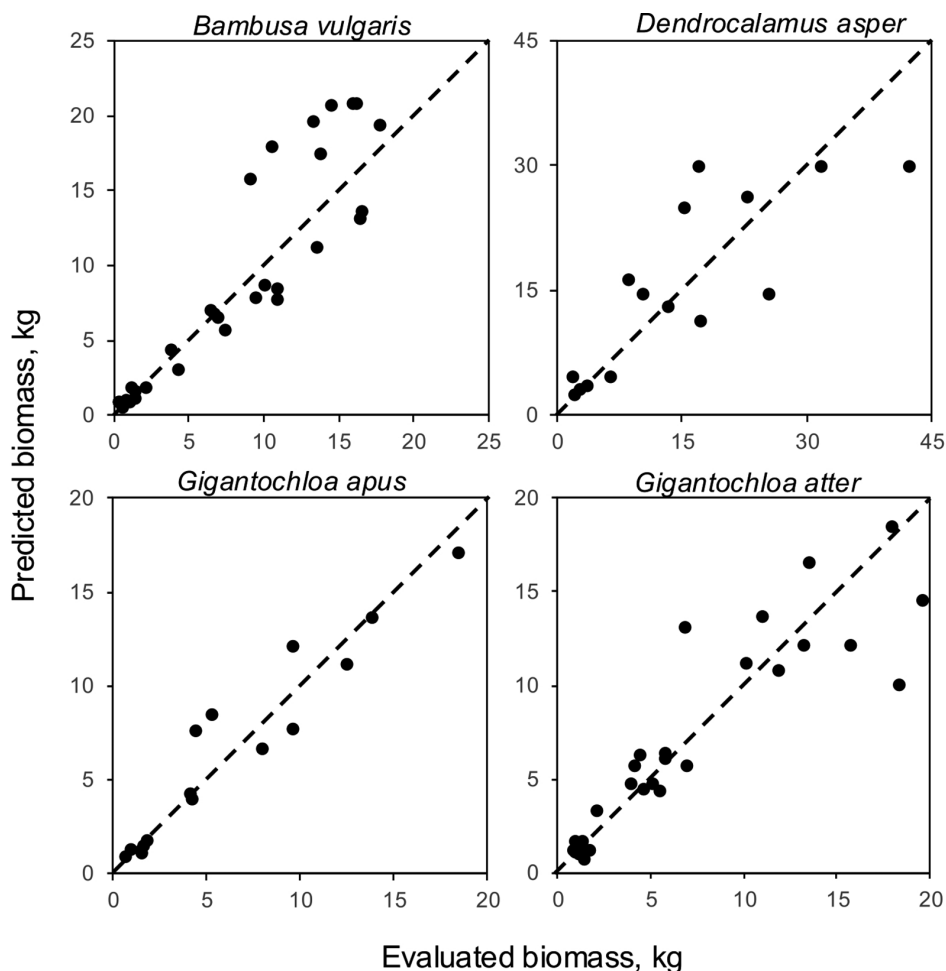


Fig. 2. Relationship between observed and model-predicted culm biomass.

pretability of the models, these diagnostic results support the suitability of the selected models for biomass estimation.

Furthermore, predictive performance was evaluated using leave-one-out cross-validation (LOOCV) (Table 7). Positive $CV-R^2$ values indicate that all selected models performed better than predictions based solely on the mean observed biomass. The models for *G. apus* and *G. atter* showed relatively strong predictive performance, whereas the model for *D. asper* had a lower $CV-R^2$ and a higher

$CV-RMSE$. Although the sample sizes for *D. asper* and *G. apus* were relatively small (five culms per diameter class and 15 culms per species), the selected models still showed reasonable predictive performance within the range of the examined data. However, the limited sample sizes may increase uncertainty in parameter estimates and restrict the broader applicability of the models. In particular, the equation developed for *D. asper* should be applied with caution and further validated using a larger, independent dataset.

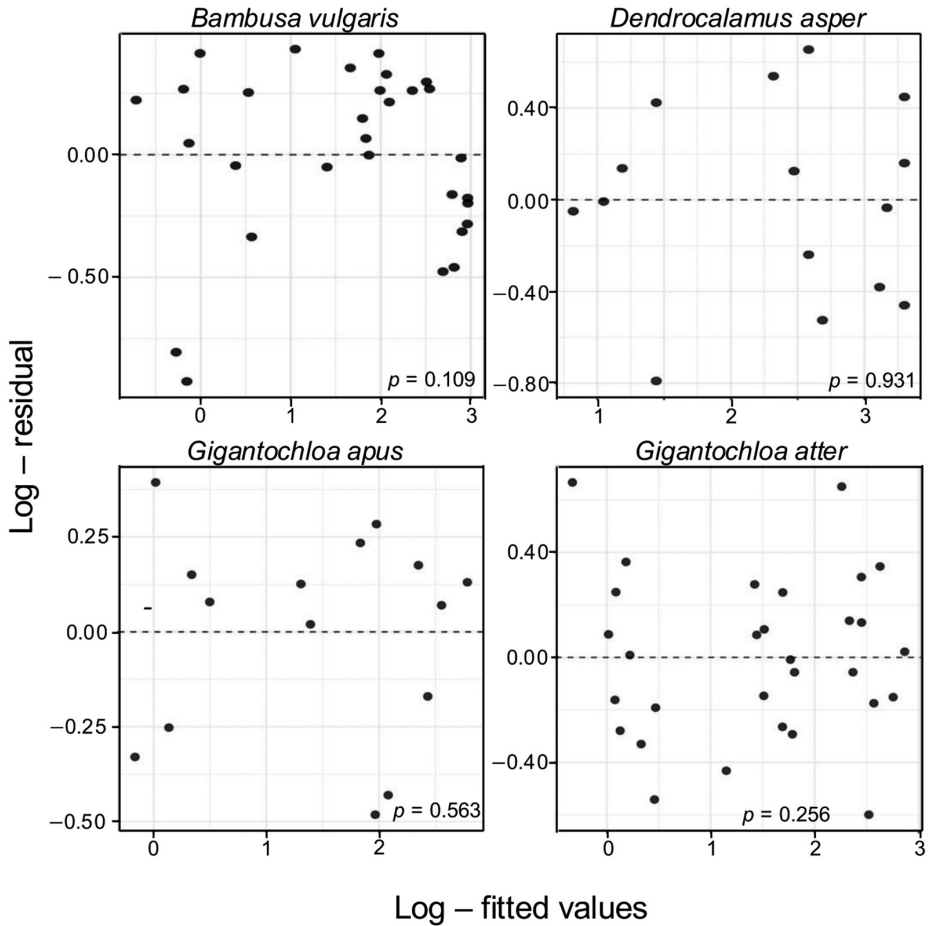


Fig. 3. Residuals versus fitted values for the selected allometric models of bamboo species.

Table 7. Leave-one-out cross-validation (LOOCV) results for the selected allometric models.

Species	Selected model	<i>n</i>	CV-R ²	CV-RMSE, kg
<i>Bambusa vulgaris</i>	<i>D+H</i>	30	0.659	3.395
<i>Dendrocalamus asper</i>	<i>D</i>	15	0.554	7.645
<i>Gigantochloa apus</i>	<i>D+H</i>	15	0.836	2.108
<i>Gigantochloa atter</i>	<i>D+R</i>	30	0.777	2.745

Note: *D* – culm diameter; *H* – culm height; *R* – number of internodes; *n* – number of sampled culms. CV-R² – cross-validated coefficient of determination obtained from leave-one-out cross-validation (LOOCV); CV-RMSE – cross-validated root mean square error, expressed in kg. Model combinations indicate the predictor variables included in the selected allometric model.

Overall, these results confirm that the selected allometric models for culm biomass are species-specific. Culm diameter remained the main predictor of culm biomass, while the contributions of culm

height and number of internodes varied according to the morphological characteristics of each species. The final species-specific allometric equations are presented in Table 8.

Table 8. Selected allometric equations for each bamboo species.

Species	Model	Equation
<i>Bambusa vulgaris</i>	$D+H$	$Y = 0.036 \cdot D^{1.548} \cdot H^{0.961}$
<i>Dendrocalamus asper</i>	D	$Y = 0.107 \cdot D^{2.162}$
<i>Gigantochloa apus</i>	$D+H$	$Y = 0.021 \cdot D^{1.261} \cdot H^{1.254}$
<i>Gigantochloa atter</i>	$D+R$	$Y = 0.476 \cdot D^{2.705} \cdot R^{-0.792}$

Note: Y – culm biomass; D – culm diameter at 1.3 m height; H – culm height; R – number of internodes. Model combinations indicate the predictor variables included in each allometric model (e.g. $D+H$ = diameter and height; $D+R$ = diameter and number of internodes).

Conclusions

The relationship between culm morphology and culm biomass differs among bamboo species. Culm diameter is the most consistent variable for estimating culm biomass, while the contributions of culm height and number of internodes depend on the characteristics of each species. The best allometric models use culm diameter for *Dendrocalamus asper*, a combination of diameter and culm height for *Bambusa vulgaris* and *Gigantochloa apus*, and a combination of diameter and number of internodes for *Gigantochloa atter*. Thus, the resulting allometric models are species-specific and can be used to predict culm biomass at the individual culm level in a practical and non-destructive manner. The proposed equations may serve as a basis for future studies on bamboo carbon stocks, sustainable management and stand-level biomass assessment.

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