



Empirical allometric models for estimating aboveground biomass of *Bambusa teres* and *Bambusa tulda* in non-forest areas of Nepal

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Abstract The ability of bamboo to store carbon in its biomass varies depending on species, site conditions, and management practices. In Nepal, bamboo is widely distributed outside forest areas, often with little or no management, making it essential to develop biomass models to quantify its carbon stock potential in such settings. Therefore, this study aims to develop species-specific aboveground biomass models for *Bambusa teres* Buch.-Ham. ex Munro and

Bambusa tulda Roxb. in non-forest areas of Nepal. A total of 104 culms (54 *B. teres*, 50 *B. tulda*) were sampled; diameter at breast height (DBH) and height ranged 4.0–9.4 cm and 8.3–22.4 cm in *B. teres*, 4.3–10.5 cm and 7.0–20.7 cm in *B. tulda*. Various regression models (linear, power, and exponential) were tested using DBH and height as independent variables and biomass components (foliage, branch, culm, and total aboveground biomass) as dependent variables. Due to the small sample size, the leave-one-out cross-validation method was used for model validation. Our findings indicate that *B. tulda* had significantly higher mean DBH, foliage, and branch biomass than *B. teres*. The power model incorporating both DBH and height (M9) performed best (adj. $R^2 > 0.80$) for predicting culm biomass and total aboveground biomass in both species. However, none of the models accurately predicted foliage biomass and branch biomass (adj. $R^2 < 0.55$), suggesting that allometric models may not be suitable for these components. This study aids in quantifying bamboo carbon and establishing a database for studied species, facilitating Nepal's entry into the carbon credit market. We recommend development of species- and age-specific allometric models for other bamboo species along with belowground biomass models to enhance bamboo carbon quantification in non-forest settings in Nepal.

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Introduction

Bamboo, known as "Green Gold" and "Poor Man's Timber," belongs to the grass family Poaceae. It is one of the fastest-growing plants due to its rhizome system, with species like *Dendrocalamus giganteus* and *Phyllostachys edulis* growing up to 91 cm per day (Dransfield & Widjaja 1995). Globally, over 1,718 species are recognized (Vorontsova et al. 2016), classified into monopodial, sympodial, and amphipodial types (Lobovikov et al. 2007). It occurs naturally across tropical, subtropical, and temperate regions of Africa, Asia, and the Americas, covering about 37 million hectares, or 3.2% of global forest area (FAO 2020). Bamboo grows well across a wide range of land uses (forests, farmlands, riverbanks, roadsides, and urban areas), soil types, and weather conditions (rainfall and temperature), highlighting its strong adaptability (Ahmad et al. 2021; Koepke-Hill et al. 2020).

Accurate biomass measurement is essential for estimating carbon stocks and mitigating climate change (Yuen et al. 2017). Carbon data supports global climate models and initiatives like REDD+ (Reducing Emissions from Deforestation and Forest Degradation), which rely on precise carbon stock reporting to guide climate strategies. Biomass estimation can be done using destructive or non-destructive methods (Huy and Long 2019). Destructive methods provide highly accurate data; however, they are resource-intensive, time-consuming, and impractical for large-scale studies (Pandey et al. 2022). Non-destructive methods, including allometric models, remote sensing, and satellite imagery, are more practical. Allometric models, which relate measurable tree characteristics such as diameter at breast height (DBH) and height to biomass, are widely used because of its cost effectiveness for estimating measurements without requiring repeated destructive sampling (Kuyah and Rosenstock 2015). However, their effectiveness largely depends on species-specific models that account for variations in tree structure and growth patterns. Biomass estimation is influenced by several species-specific functional traits factors such as wood density, branch architecture, and growth rate, which vary significantly across species (Mensah et al. 2016). Applying general allometric equations to a diverse set of species often leads to inaccurate estimates, as these

equations may not capture the unique characteristics of each species (Chave et al. 2004; Kaushal et al. 2022). Vorster et al. (2020) studied variability and uncertainty in biomass estimates from the tree to landscape scale where they reported that allometric equations contribute 30–75% of total uncertainty. Therefore, developing species-specific allometric models is crucial for improving the accuracy of biomass and carbon stock predictions, especially in heterogeneous ecosystems where variability among species is high (Martínez-Sánchez et al. 2020). In addition, site-specific models are equally important. Models developed for bamboo plantations or natural forests may not accurately represent stands in non-forest environments such as farmlands, agroforestry systems, roadsides, or riverbanks, where growing conditions, stand structures, and management practices differ substantially (Jember et al. 2023). Variations in soil fertility, moisture availability, planting density, and disturbance regimes in these settings can influence bamboo growth patterns, leading to biases if forest- or plantation-derived models are applied without adjustment. Therefore, developing site-specific and species specific allometric models is critical for reliable forest management practices and carbon accounting in global climate change mitigation efforts (Anitha et al. 2015; Ayer et al. 2024).

Allometric model development typically relies on fitting statistical relationships between easily measurable parameters, such as DBH and height, and biomass. Different regression forms, including linear, power, and exponential models—are commonly used depending on the nature of the biological relationship (Chave et al. 2004; Abebe et al. 2023; Kaam et al. 2023). Power functions are often preferred because tree and bamboo biomass tend to scale nonlinearly with size dimensions (Huy and Long 2019), but linear and exponential models are also tested to identify the best fit and minimize prediction errors (Yuen et al. 2017). Therefore, comparing multiple model forms ensures that the most accurate and biologically realistic equations are selected for biomass estimation.

In Nepal, 12 genera and more than 53 species of bamboo have been reported across different physiographic regions inside and outside forest area (Das 2002; Ayer et al. 2023). These bamboo species can have significant carbon storage capacity, however

quantifying their biomass and carbon stock potential is a great challenge in Nepal (Ayer et al. 2024). This is because direct measurement or estimation of biomass using destructive methods requires significant human and financial resources and is unfriendly to the environment (Huy and Long 2019), while the non-destructive or allometric models (indirect method) are yet to be developed for Nepal (Ayer et al. 2024). Previous studies in Nepal on allometric model development have been focused on the forest tree species only (Bhandari and Neupane 2014; Sharma et al. 2017; Aryal et al. 2023, 2024). Unlike other woody species, allometric models for estimating the biomass and carbon stock of grass species, including bamboo, are scanty (Oli 2005a, b). Ayer et al. (2024) studied the impact of elevation and aspect on bamboo carbon in Thailand using allometric model developed by Yuen et al. (2017). However, these models may not reliably estimate biomass for bamboo species in Nepal due to differences in species, land-use history, management practices, and topographic, edaphic and climatic conditions (Yuen et al. 2016). Moreover, site-specific models are more accurate than generalized ones. Therefore, this study aims to develop allometric models for biomass estimation of two Nepalese bamboo species (*Bambusa teres* Buch.-Ham. ex Munro and *Bambusa tulda* Roxb.) which are widely distributed outside forest areas. We hypothesized that power models with DBH and height can predict aboveground biomass better than other model forms as reported by previous studies for different bamboo species (Huy and Long 2019; Abebe et al. 2023; Tesema et al. 2024). Furthermore, foliage and branch biomass prediction could be less accurate as branching pattern can be largely affected by habitat conditions, such as light, clump crowding, and culm position within a clump (Xayalath et al. 2019). Developed specific allometric models for the studied bamboo species can be used for future research to estimate the biomass and carbon storage capacity in a cost-effective and eco-friendly way.

Materials and methods

Study area

The study was conducted across Nepal, a country with diverse climate, physiography, geology,

and vegetation. Covering 1,47,181 km², Nepal lies between 26°22' to 30°27' N latitude and 80°4' to 88°12' E longitude (Fig. 1). Despite its small size, the elevation varies significantly, ranging from 60 m in the south to 8,848 m in the north within less than 200 km. Nepal is divided into five physiographic regions based on elevation: Terai, Siwaliks (Churia), Middle Mountains, High Mountains, and High Himalaya (Upreti 1999). The Terai is a low-lying plain, while the other regions consist of hilly and mountainous terrain, with the High Himalaya featuring snow-covered peaks. The country's climate ranges from subtropical to arctic, and annual precipitation varies from less than 300 mm to over 5,000 mm, with significant differences in intensity and distribution (Nayava 1980). Some high mountain valleys experience low rainfall due to the rain shadow effects. Nepal's geology includes recent alluvial deposits in the Terai, and mudstones, sandstones, and conglomerates in the Siwaliks, which are prone to erosion (Adhikari and Ojha 2021). The Middle and High Mountains consist of phyllites, granites, and limestones, with shallow soils, while the High Himalaya is predominantly rocky (Adhikari and Ojha 2021). In Nepal, the primary land use is forest cover (41.69%), followed by cropland (24.21%) and grassland (13.27%), with around 20% of land occupied by snow, bare rock, water bodies, and other non-vegetated areas (FRTC 2022).

Bamboo is distributed all over Nepal where one or more species of bamboo can be encountered in 73 of the 77 districts in Nepal (Joshi and Amatya 1999). The natural range of bamboo in Nepal extends from the Terai (flat plain – 50 m above sea level asl) to the high mountains (3500 m asl) (Fig. 6) (Das 1988; Stapleton 1994; Ayer et al. 2023). For this study, two commonly found bamboo species, i.e. *Bambusa teres* and *Bambusa tulda* were selected. They were reported from 16 districts of Nepal which are Banke, Dhankuta, Dhanusha, Gorkha, Ilam, Kailali, Kavre, Khotang, Makwanpur, Morang, Ramechhap, Sankhuwasabha, Saptari, Sarlahi, Siraha, and Udayapur. Most of the bamboo plots in the study were in agricultural land. Farmers often believe that bamboo requires minimal care and management (Ghimire 2008). As a result, bamboo species outside forested areas typically lack management practices such as fertilization, thinning, and pruning. Bamboo culms are generally harvested when they reach their

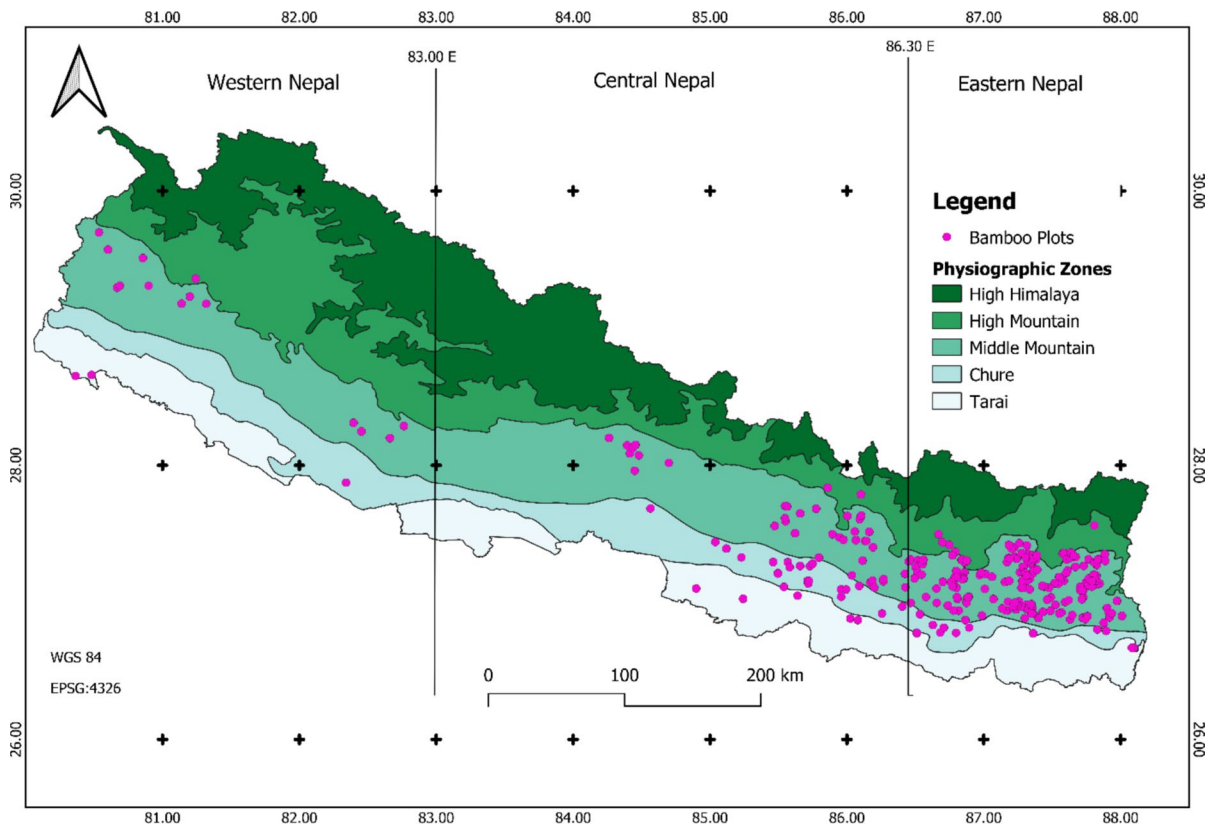


Fig. 1 Study area map of Nepal showing bamboo plots for *B. teres* and *B. tulda* in non-forest area across different physiographic regions. Physiographic regions are divided into five levels based on the elevation range as: High Himalaya

(> 4000 m asl), High Mountain (3300–4000 m asl), Middle Mountain (1200–3300 m asl), Chure (130–1200 m asl) and Terai (< 130 m asl)

maximum size and strength, usually between 3 and 5 years of age (Ayer et al. 2023). In general, the study plots consisted of naturally occurring bamboo clumps, dispersed across agricultural, marginal, degraded, and sloped lands, with no association with other plant species.

Sampling design and measurement

The sample plots for the bamboo resources assessment outside the forest area were designed and selected adopting a two-phase stratification approach (FRTC 2023). For the bamboo resource inventory in Nepal, circular sample plots of radius 56.42 m (1 ha area) were designed. A total of 650 plots were inventoried for different species of bamboo outside forest area across Nepal. This study includes only two major bamboo species: *B.*

teres and *B. tulda*. A destructive sampling method was employed for harvesting bamboo culms for *B. teres* and *B. tulda* species outside forest area across Nepal following Yuen et al. (2017) and Huy and Long (2019). Harvesting excessive culms is not recommended when developing allometric models, as it can negatively impact ecosystems and practicality. Conversely, including too many small culms may introduce bias (Duncanson et al. 2015). Roxburgh et al. (2015) suggest that for accurate biomass predictions, with a standard deviation of less than 5%, a sample size between 17 and 95 individuals is required, depending on the model. The International Bamboo and Rattan Organization (INBAR) manual also advises harvesting 30–50 representative culms to create species-specific allometric models (Huy and Long 2019). Therefore, a total of 54 (*B. teres*) and 50 (*B. tulda*) culms

along with samples of other bamboo species were harvested for biomass estimation from 650 plots across Nepal. In each plot, the dendrometric variables such as DBH and culmination height were recorded for each culm using diameter tape and Vertex and Transponder respectively. The age of bamboo was determined using its morphological features described in bamboo resource inventory report by FRTC (2023). Each felled culm was categorized into different components (leaves, branches, and culms) as per Huy and Long (2019). Additionally, three representative culm discs of varying sizes were taken from the base (just above 0.3 cm or stump height), middle, and top of each culm. The fresh weight of each bamboo component was recorded on-site. Following this, all samples were placed in labeled paper bags, with each label including the sample plot/clump code, culm code, component type, and sample name.

Laboratory analysis and biomass calculations

The samples were transported to the laboratory and dried at a temperature of 105 °C for 48 h, or until a stable dry weight was achieved (Pillow 1958). The total dry weight or biomass of each bamboo component was then calculated using Eq. 1 as outlined by FAO (2012).

$$TDW = TFW \times \frac{SDW}{SFW} \quad (1)$$

Where, TDW=total dry weight or biomass; TFW=total fresh weight; SDW=sub-sample dry weight; SFW=sample fresh weight. The sum of the entire components represents the oven-dried weight or total aboveground biomass (AGB) of the bamboo.

Statistical analysis

The raw data was organized and entered a Microsoft Excel spreadsheet, and the analysis was performed using R statistical software, with a significance level (α) of 0.05. Prior to conducting the statistical analysis, Shapiro–Wilk test was used to assess normality. The bamboo biometric data were found to be normally distributed ($p > 0.05$). Welch's t-test was applied to

evaluate differences in biometric parameters between two studied bamboo species. Regression analysis was then used to model the relationship between the dependent variable (bamboo biomass of each component) and the independent variables (DBH and height).

Model development, selection and validation

We tested 9 candidate models (Table 1) to fit our data, which included combinations of DBH alone, height alone, and both DBH and height in linear (Model 1–3), exponential (Model 4–6) and power (Model 7–9) forms (Huy and Long 2019; Kaushal et al. 2022; Abebe et al. 2023; Kaam et al. 2023; Tesema et al. 2024). For model fitting, the entire dataset was utilized to ensure that all available data contributed to the development of robust equations. Models were fitted using parameter estimation method. Ordinary least squares (OLS) was applied for linear model fitting, while nonlinear least squares (NLS) was performed for nonlinear models, both minimizing the sum of squared residuals to achieve the best fit. For the NLS models, starting values were applied by default based on the software's optimization procedure. To evaluate the quality of fit, adjusted R^2 (Anderson-Sprecher 1994) and akaike information criterion (AIC) (Akaike 1973) were calculated (Table 2). Adjusted R^2 provided a measure of how well the models explained the variability in biomass, while AIC was used to compare the relative performance of the models, penalizing for complexity to avoid overfitting.

Table 1 Candidate models for developing allometric models for estimating bamboo biomass

Model Code	Model form	Equation
M1	Linear	biomass = a + b. DBH
M2	Linear	biomass = a + b. height
M3	Linear	biomass = a + b. DBH + c. height
M4	Exponential	Biomass = a. exp ^{b. DBH}
M5	Exponential	Biomass = a. exp ^{b. Height}
M6	Exponential	Biomass = a. exp ^(b. DBH + c. Height)
M7	Power	Biomass = a. DBH ^b
M8	Power	Biomass = a. Height ^b
M9	Power	Biomass = a. DBH ^b . Height ^c

a, b and c are allometric coefficients β_0 , β_1 and β_2 respectively

Table 2 Summary of statistical criterion for model fitness evaluation

Statistic	Formula	Interpretation
Adj.R ²	$1 - \frac{\sum_{i=1}^n (Y_i - \hat{Y})^2}{\sum_{i=1}^n (Y_i - \bar{Y})^2}$	Closer to 1, better
AIC	$2p - 2\ln(L)$	Lower is better
RMSE	$\sqrt{\frac{1}{n} \sum_{i=1}^n \left(\frac{Y_i - \hat{Y}}{Y_i} \right)^2}$	Lower is better
RRMSE (%)	$\left(\frac{RMSE}{\bar{Y}} \right) * 100$	Lower is better
PBias(%)	$\frac{1}{n} \sum_{i=1}^n \left(\frac{Y_i - \hat{Y}}{Y_i} \right) * 100$	Lower is better

Y_i : actual data, $\bar{Y}$: mean of actual data, $\hat{Y}$: predicted data by model, $\ln$: natural logarithm, L : likelihood of fitted model, p : number of parameters, n : number of observations

Given the small sample size in our study, leave-one-out cross-validation (LOOCV) was utilized to validate the models. LOOCV is particularly suitable for small datasets, as it systematically leaves out one observation at a time for validation, ensuring that all data points are used for both training and testing. The validation metrics included root relative mean square error (RRMSE) (Legates and McCabe 1999) to assess prediction accuracy and percentage bias (Horn and Korn 1989) to quantify systematic prediction errors (Table 2). The model having all model parameter estimates significant and having higher Adj. R², lower RMSE, AIC and bias was considered as the best model for estimating bamboo biomass.

To test the effect of species on variation in allometry, we fitted separate power models for each species using nonlinear least squares regression for culm biomass and total AGB. Next, we assessed whether there is a significant difference in the allometric relationships between species by conducting an analysis of variance (ANOVA). Specifically, we

compared the species-specific models to a common model that assumes identical allometric parameters for all species. The comparison was done using the anova() function in RStudio, which evaluates the reduction in residual sums of squares between the models. A p -value below 0.05 would indicate a significant effect of species on allometric variation, suggesting that species-specific differences are important in explaining biomass variation.

Comparison with previously developed models

In this study, we compared our biomass estimation models with several previously developed equations to assess how well they applied to bamboo stands outside forest areas (Table 1). As our model was specifically developed for bamboo in non-forest environments, it was important to evaluate its performance against models that were developed for bamboo in plantation and research center settings, which may have different environmental conditions. The models we reviewed, summarized in Table 3, were focused on estimating biomass for various bamboo components (culm, branch, foliage, and total AGB) using predictor variables such as DBH and Height. Since we did not find a specific equation for *B. teres*, we used the genus-level model developed for *B. nutans*. To evaluate the performance of previously developed models on our dataset, we calculated adjusted R², Relative Root Mean Square Error (RRMSE) and Mean Relative Error (MRE) to assess goodness of fit, prediction accuracy, and average deviation from observed values. Additionally, a paired t-test was conducted to determine if significant differences existed between the observed biomass and biomass estimates from these models in our dataset.

Table 3 Summary of biomass model equations used for comparison

Authors	Species Studied	Component	Model Equation	Site	Country
Puangchit et al. (2019)	<i>B. nutans</i> <i>B. tulda</i>	Branch Foliage Culm Total AGB	a.DBH ^b	Plantation	Myanmar
Rawat et al. (2018)	<i>B. tulda</i>	Culm	a + b.DBH + c.Height	Research centre	India
Yuen et al. (2017)	<i>B. nutans</i>	Total AGB	a.DBH ^b	Research centre	Thailand
Kaushal et al. (2022)	<i>B. nutans</i>	Total AGB	a.DBH ^b .Height ^c	Not specified	India

Results

Biometric parameters of sampled bamboo

The DBH and height of *B. teres* ranged from 4 to 9.4 cm and 8.3 to 22.4 cm, respectively, while *B. tulda* had a DBH range of 4.3 to 10.5 cm and a height range of 7 to 20.7 cm. The comparison of biometric attributes between *B. teres* and *B. tulda* revealed significant differences in some parameters (Table 4). *B. tulda* had a significantly larger culm DBH than *B. teres*. However, no significant difference was observed in culm height between the two species ($p > 0.05$). *B. tulda* exhibited significantly higher branch and foliage biomass compared to *B. teres* ($p < 0.05$). Although, *B. teres* had a higher culm biomass than *B. tulda*, the difference was not statistically significant ($p > 0.05$). Similarly, the total AGB also did not show any significant difference between the two species ($p > 0.05$).

The proportion of green weight components differed between *B. teres* and *B. tulda* (Fig. 2). *B. teres* allocated a higher proportion of its total biomass to the culm compared to *B. tulda*. In contrast, *B. tulda* allocated more biomass to branches and foliage compared to *B. teres*.

Allometric models for biomass estimation of two species.

In both species, models incorporating DBH and height in combination (M3, M6, M9 and M12) performed better (adj $R^2 > 0.8$) for culm and total AGB biomass estimation compared to models using DBH or height alone (Tables 5 and 6). For foliage biomass for *B. teres* and branch biomass estimation for both

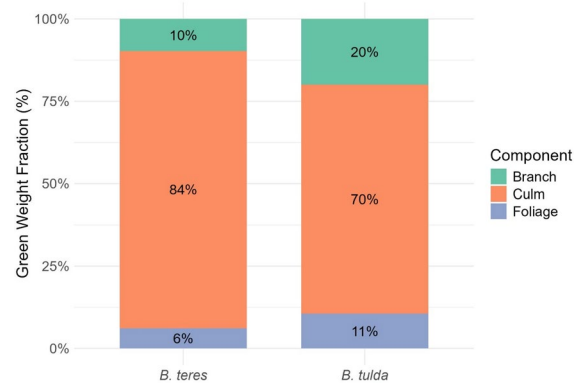


Fig. 2 Distribution of percentage (%) share of green weight of culm, branch and foliage in different bamboo species

species, DBH alone was a better predictor. However, adj R^2 for best model was less than 0.53. As a single predictor variable, DBH alone was a better predictor than height alone, as indicated by its higher adj. R^2 , lower AIC, and RMSE values. This trend is also evident from the scatterplots (Fig. 3). However, overall performance of models using only DBH and height as predictor was poor (adj. $R^2 < 0.8$).

All model forms developed from the combination of DBH and height performed reasonably well for culm biomass and total AGB (adj. $R^2 > 0.8$) (Tables 5 and 6). Based on higher adj. R^2 , lower AIC values, and lower RMSE, the power model (M9) was found to be the best model form for the culm and total AGB estimation for both species. Scatter plot of culm and total AGB with DBH and height also shows clear nonlinear relationship (Fig. 3). Log-linear model (M10) was best model for estimating foliage and branch biomass for *B. teres* whereas exponential model M6 and log-linear model M10 was the best

Table 4 Descriptive statistics of measurements of bamboo variables (mean $\pm$ st. error)

Component	<i>B. teres</i>	<i>B. tulda</i>	t-value	p-value
DBH (cm)	6.66 $\pm$.199	7.34 $\pm$ 0.225	-2.242	0.03*
Height (cm)	13.89 $\pm$.477	13.20 $\pm$ 0.509	0.989	0.32 ^{ns}
Foliage Biomass (kg)	0.68 $\pm$.098	1.465 $\pm$.106	-5.381	<0.01**
Branch Biomass (kg)	1.14 $\pm$.087	2.834 $\pm$ 0.181	-8.424	<0.01**
Culm Biomass (kg)	10.26 $\pm$.708	9.88 $\pm$ 0.764	0.361	0.71 ^{ns}
Total AGB (kg)	12.09 $\pm$.794	14.18 $\pm$ 0.927	-1.712	0.08 ^{ns}

Statistical analyses are significant at 95% confidence interval. ***Significant at $p < 0.001$; **Significant at $p < 0.01$; *Significant at $p < 0.05$; and ns (non-significant) at $p > 0.05$. DBH: Diameter at breast height; Height: Culmination height; AGB: Aboveground biomass of bamboo. Also, biomass here represents oven dry biomass per culm

Table 5 Summary of allometric models for *B. teres* bamboo biomass components estimation

Models	Parameter			Adj. R ²	AIC	RRMSE	PBias	p-value
	a	b	c					
<i>Culm biomass</i>								
M1	11.004***	3.191***	—	0.80	247.87	23.00	0.10	<0.01
M2	−6.414***	1.200***	—	0.64	279.09	30.80	0.10	<0.01
M3	−12.35***	2.317***	0.515***	0.86	229.81	19.69	0.00	<0.01
M4	1.165***	0.311***	—	0.80	246.27	22.71	0.39	<0.01
M5	2.509***	0.097***	—	0.60	285.03	32.65	0.88	<0.01
M6	1.081***	0.240***	0.039***	0.87	226.67	19.79	0.78	<0.01
M7	0.153**	2.185***	—	0.81	245.01	22.51	0.00	<0.01
M8	0.171*	1.546***	—	0.63	280.67	31.38	0.58	0.04
M9	0.073**	1.646***	0.667***	0.88	222.21	18.52	0.10	<0.01
<i>Foliage biomass</i>								
M1	−0.561 ^{ns}	0.187**	—	0.11	113.71	101.47	0.00	<0.01
M2	0.487 ^{ns}	0.014 ^{ns}	—	−0.03	122.01	107.35	0.00	0.61
M3	−0.348 ^{ns}	0.326***	−0.081*	0.18	110.41	97.06	0.00	<0.01
M4	0.107 ^{ns}	0.268**	—	0.11	113.73	102.94	1.47	0.20
M5	0.55 ^{ns}	0.016 ^{ns}	—	−0.04	122.07	107.35	0.00	0.09
M6	0.124 ^{ns}	0.119***	−0.097*	0.19	109.87	98.53	1.47	0.20
M7	0.018 ^{ns}	1.896*	—	0.12	113.6	102.94	0.00	0.50
M8	0.284 ^{ns}	0.339 ^{ns}	—	−0.03	121.84	107.35	0.00	0.51
M9	0.064 ^{ns}	3.108**	−1.375 ^{ns}	0.17	110.83	98.53	0.00	0.54
<i>Branch biomass</i>								
M1	−0.505 ^{ns}	0.247***	—	0.30	88.58	47.37	0.00	<0.01
M2	0.247 ^{ns}	0.064 ^{ns}	—	0.09	102.33	54.39	0.88	<0.01
M3	−0.46 ^{ns}	0.276***	−0.017 ^{ns}	0.29	90.22	48.25	0.00	<0.01
M4	0.290**	0.199***	—	0.27	90.26	49.12	0.88	<0.01
M5	0.613**	0.044*	—	0.07	103.69	55.26	0.88	<0.01
M6	0.299**	0.233***	−0.018 ^{ns}	0.27	91.50	50.00	0.88	<0.01
M7	0.078 ^{ns}	1.408***	—	0.29	88.94	48.25	0.88	0.13
M8	0.162 ^{ns}	0.743*	—	0.10	101.92	53.51	0.88	0.20
M9	0.094 ^{ns}	1.573***	−0.193 ^{ns}	0.28	90.60	49.12	0.88	0.19
<i>Total AGB</i>								
M1	12.071***	3.626***	—	0.82	254.04	20.60	0.08	<0.01
M2	−5.68**	1.279***	—	0.57	300.57	31.76	0.17	<0.01
M3	13.158***	2.920***	0.416**	0.85	245.28	19.19	0.08	<0.01
M4	1.523***	0.297***	—	0.82	254.33	20.84	0.41	<0.01
M5	3.443***	0.087***	—	0.53	306.62	33.75	0.91	<0.01
M6	1.452***	0.250***	0.025**	0.85	246.46	20.35	0.83	<0.01
M7	0.219**	2.086***	—	0.83	251.83	20.26	0.08	<0.01
M8	0.310*	1.387***	—	0.56	302.04	32.26	0.66	0.04
M9	0.133**	1.713***	0.457***	0.86	241.12	18.78	0.25	<0.01

Statistical analyses are significant at 95% confidence interval. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; and ns (non-significant) $p > 0.05$. AGB: aboveground biomass of bamboo; a, b and c are the model's fitted parameters; RMSE: Root mean square error; AIC: Akaike information criterion; and Adj. R²: coefficient of determination. Bold letters represent the best model for this study

model for biomass estimation for foliage and branch in *B. tulda*, respectively. However, models' overall performance for foliage and branch biomass was extremely poor. The best models for each component

of both species are highlighted with bold letters in Tables 4 and 5. Residual plot for best models for foliage and branch biomass clearly shows overprediction

Table 6 Summary of allometric models for *B. tulda* bamboo biomass components estimation

Models	Parameters			Adj R ²	AIC	RRMSE (%)	PBias (%)	p-value
	a	b	c					
Culm biomass								
M1	11.009***	2.847***	–	0.69	254.33	30.67	0.20	<0.01
M2	–6.908***	1.272***	–	0.71	252.11	29.86	0.20	<0.01
M3	11.431***	1.569***	0.743***	0.80	234.78	25.00	0.30	<0.01
M4	1.041***	0.293***	–	0.72	249.61	29.25	–0.20	<0.01
M5	1.822***	0.121***	–	0.72	249.62	29.15	–0.30	<0.01
M6	1.057***	0.160***	0.072***	0.83	224.64	22.67	–0.40	<0.01
M7	0.091 ^{ns}	2.316***	–	0.72	249.80	29.45	0.40	0.05
M8	0.095*	1.782***	–	0.72	249.41	29.15	0.30	0.04
M9	0.045**	1.240***	1.103***	0.84	224.89	22.67	0.51	<0.01
Foliage biomass								
M1	–0.139 ^{ns}	0.219***	–	0.18	105.98	47.10	0.00	<0.01
M2	1.510***	–0.003	–	–0.04	118.15	52.56	–0.68	0.91
M3	–0.034 ^{ns}	0.536***	0.184***	0.52	80.79	36.86	0.00	<0.01
M4	0.554**	0.130**	–	0.16	107.61	48.46	–0.68	0.01
M5	1.502***	–0.002 ^{ns}	–	–0.04	118.16	52.56	–0.68	<0.01
M6	0.562***	0.367***	0.136***	0.53	79.79	36.18	–1.37	<0.01
M7	0.186 ^{ns}	1.037**	–	0.18	106.07	47.10	–0.68	0.14
M8	1.204 ^{ns}	0.077 ^{ns}	–	–0.04	118.05	52.56	–0.68	0.14
M9	0.448 ^{ns}	2.959***	1.854***	0.53	79.68	36.18	–0.68	0.06
Branch biomass								
M1	–0.929 ^{ns}	0.513***	–	0.38	145.41	36.34	0.00	<0.01
M2	0.396 ^{ns}	0.185***	–	0.24	155.93	40.23	0.35	<0.01
M3	–0.945 ^{ns}	0.465***	0.028 ^{ns}	0.37	147.20	36.70	0.00	<0.01
M4	0.672***	0.190***	–	0.41	143.59	35.99	0.35	<0.01
M5	1.117***	0.068***	–	0.26	154.43	40.23	0.35	<0.01
M6	0.645***	0.155**	0.022 ^{ns}	0.41	144.25	36.70	0.35	<0.01
M7	0.166 ^{ns}	1.415***	–	0.39	144.75	36.34	0.35	0.07
M8	0.285 ^{ns}	0.890***	–	0.24	156.14	40.93	0.35	0.09
M9	0.137 ^{ns}	1.224**	0.221 ^{ns}	0.39	146.17	37.05	0.71	0.09
Total AGB								
M1	12.078***	3.578***	–	0.75	263.81	23.55	0.14	<0.01
M2	–5.000*	1.454***	–	0.62	284.11	28.63	0.07	<0.01
M3	12.411***	2.570***	0.586**	0.79	255.88	21.51	0.21	<0.01
M4	2.032***	0.254***	–	0.77	260.08	22.78	–0.21	<0.01
M5	3.672***	0.098***	–	0.63	283.16	28.42	–0.14	<0.01
M6	2.008***	0.178***	0.043***	0.81	249.34	20.31	–0.21	<0.01
M7	0.259**	1.984***	–	0.77	259.94	22.78	0.21	0.01
M8	0.382*	1.393***	–	0.63	283.37	28.56	0.28	0.03
M9	0.170**	1.390***	0.624***	0.82	248.38	20.17	0.42	<0.01

Statistical analyses are significant at 95% confidence interval. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; and ns (non-significant) $p > 0.05$. AGB: aboveground biomass of bamboo; a, b and c are the model's fitted parameters; RMSE: Root mean square error; AIC: Akaike information criterion; and Adj. R²: coefficient of determination

for both species where culm and total AGB residual plots shows random distributions of residual (Fig. 4).

We tested effect of species variation on allometric models using ANOVA (Table 7). We found that the species-specific model significantly improved the fit compared to the common model for both culm

biomass and total AGB, as indicated by the reduction in residual sum of squares for both components.

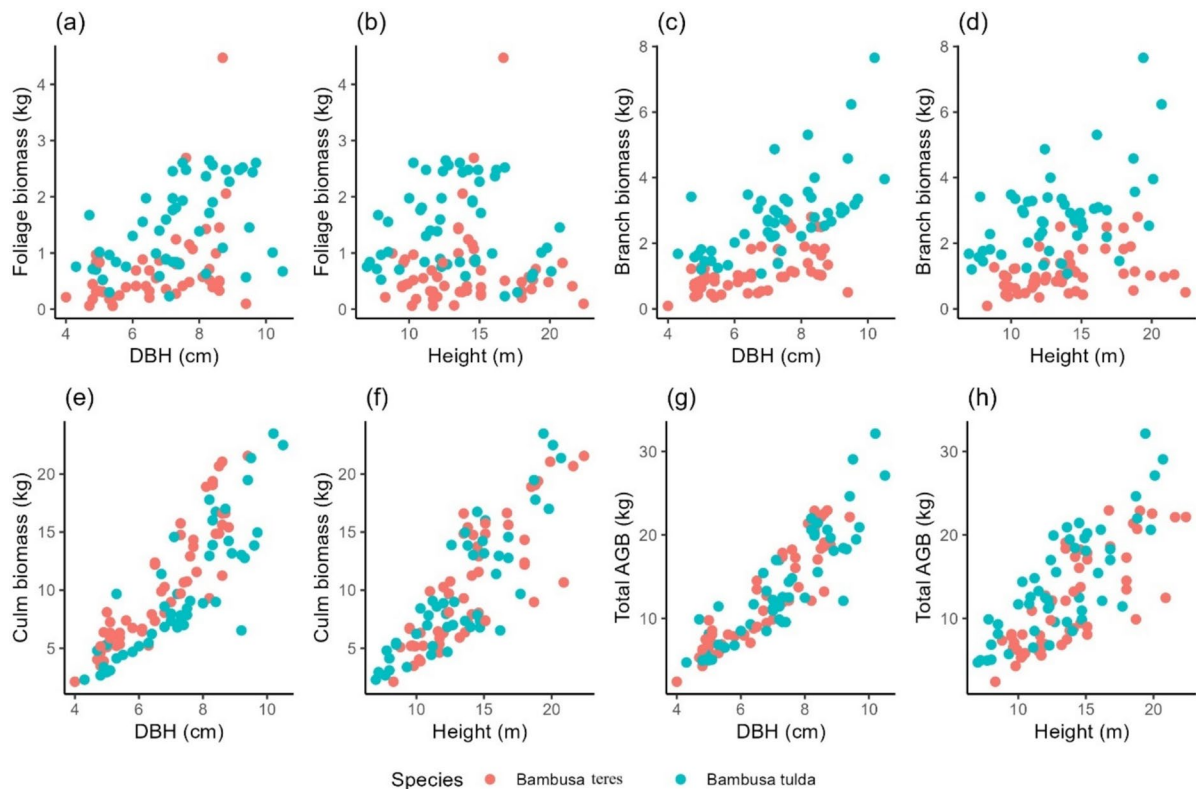


Fig. 3 Relationship between foliage, branches, culm and total AGB with bamboo DBH at 1.3 m and with culmination height for *B. teres* and *B. tulda*

Comparison with previously developed bamboo allometric models

Our models demonstrated higher accuracy in predicting total AGB and culm biomass components for both species compared to previously developed models in terms of prediction errors (Table 8). However, neither the previously developed foliage nor branch biomass models performed well and produced results like ours. In comparison, the previously developed models exhibited significantly higher prediction errors in our dataset, particularly for foliage and branch components, as evidenced by MRE values exceeding 70% in most cases. Additionally, t-tests revealed significant differences ($p < 0.05$) between the biomass estimates from these models and the observed values in our dataset (Table 9).

Discussion

Biometric parameters of sampled bamboo

B. tulda exhibited a significantly higher DBH compared to *B. teres*, while no significant difference was observed in height between the two species (Table 4). The observed differences in DBH could be due to difference in culm density across species (Ayer et al. 2024). Generally, there exists a negative correlation between DBH and stand density in bamboo forests (Yen and Lee 2011; Tin 2015). Higher density leads to increased competition for resources, limiting the growth of individual culms and resulting in smaller DBH (Kleinhenz and Midmore 2001; Tesema et al. 2024). Furthermore, bamboo in unmanaged forests tends to exhibit more variability in DBH due to environmental stresses and limited resource availability (Tesema et al. 2024). This is supported by Chen et al. (2016), who observed a decrease in average DBH in Moso bamboo (*Phyllostachys pubescens*) forests in

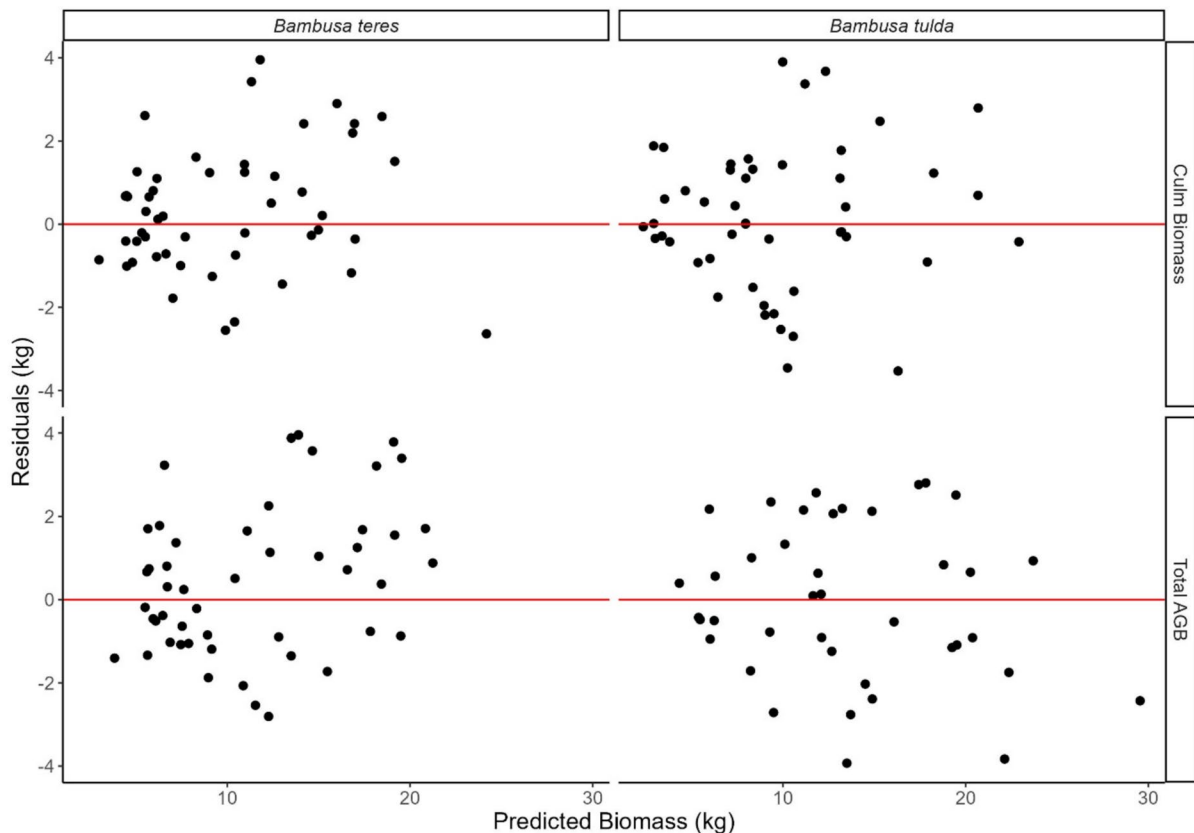


Fig. 4 Residual vs predicted biomass figure of *B. teres* and *B. tulda*. The horizontal red line serves as a baseline, helping to assess the distribution and behavior of the residuals around

zero. If the residuals are non-random, positive and negative residuals indicate over- and under-predictions, respectively

Table 7 ANOVA comparing common and species-specific models for culm biomass and total AGB to assess species variation in tree allometry. (Res: Residual, Df: degrees of freedom and SS: sum of squares)

Components	Res. Df	Res. SS	Model Df	SS difference	F-value	p-value
<i>Culm biomass</i>						
Common Model	101	457.02				
Species-Specific Model	98	391.05	3	65.97	5.51	<0.01
<i>Total AGB</i>						
Common Model	101	530.5				
Species-Specific Model	98	450.2	3	80.3	7.2	<0.01

Central Taiwan after two years of being unmanaged. In terms of culm height, we didn't observe significant difference between the two species which is consistent with findings from Mulatu et al. (2023) and Nigusse et al. (2024). Height growth could be similar between the studied species because it is primarily controlled by genetic factors, with environmental influences like soil quality, water, and climate having

less impact compared to DBH. As bamboo matures, height typically reaches a plateau and is less influenced by competition or management interventions than DBH. This aligns with the findings of Kleinhenz and Midmore (2001), who noted that height tends to be more stable across various bamboo species, regardless of environmental conditions.

Table 8 Comparison of current allometric models and the existing allometric models for bamboo

Authors	Species	Component	Adj. R ²	MRE (%)	RRMSE (%)	t-value	p-value
Puangchit et al. (2019)	<i>B. nutans</i>	Culm	0.81	63.83	77.00	15.15	$p < 0.001$
Puangchit et al. (2019)	<i>B. nutans</i>	Foliage	0.13	97.02	97.06	3.01	$p < 0.01$
Yuen et al. (2017)	<i>B. nutans</i>	Total AGB	0.83	20.03	20.76	16.15	$p < 0.001$
Kaushal et al. (2022)	<i>B. nutans</i>	Total AGB	0.86	146.46	173.28	17.73	$p < 0.001$
Puangchit et al. (2019)	<i>B. nutans</i>	Total AGB	0.83	75.16	86.27	16.11	$p < 0.001$
Puangchit et al. (2019)	<i>B. tulda</i>	Branch	0.41	74.54	80.92	5.96	$p < 0.001$
Rawat et al. (2018)	<i>B. tulda</i>	Culm	0.8	24.73	43.93	13.93	$p < 0.001$
Puangchit et al. (2019)	<i>B. tulda</i>	Culm	0.73	108.84	108.70	11.46	$p < 0.001$
Puangchit et al. (2019)	<i>B. tulda</i>	Foliage	0.15	77.5	69.39	3.1	$p < 0.01$
Puangchit et al. (2019)	<i>B. tulda</i>	Total AGB	0.77	79.48	86.18	12.98	$p < 0.001$

Table 9 Paired t test for assessing differences in biomass using current and the existing allometric models for bamboo

Component	Species	Paired Test	Predicted mean (kg)	t-value	p-value
Branch	<i>B. nutans</i>	Observed vs Puangchit et al. (2019)	3.66	-9.62	$p < 0.001$
Culm	<i>B. nutans</i>	Observed vs Puangchit et al. (2019)	16.68	-4.61	$p < 0.001$
Foliage	<i>B. nutans</i>	Observed vs Puangchit et al. (2019)	0.6	0.87	0.384
Total AGB	<i>B. nutans</i>	Observed vs Kaushal et al. (2022)	30.1	-7.77	$p < 0.001$
Total AGB	<i>B. nutans</i>	Observed vs Puangchit et al. (2019)	20.95	-5.47	$p < 0.001$
Total AGB	<i>B. nutans</i>	Observed vs Yuen et al. (2017)	12.94	-0.77	0.443
Branch	<i>B. tulda</i>	Observed vs Puangchit et al. (2019)	4.6	-5.38	$p < 0.001$
Culm	<i>B. tulda</i>	Observed vs Rawat et al. (2018)	7.36	3.05	0.003
Culm	<i>B. tulda</i>	Observed vs Puangchit et al. (2019)	19.28	-6.28	$p < 0.001$
Foliage	<i>B. tulda</i>	Observed vs Puangchit et al. (2019)	1.75	-1.60	0.112
Total AGB	<i>B. tulda</i>	Observed vs Puangchit et al. (2019)	24.78	-5.80	$p < 0.001$

We observed significant differences in foliage and branch dry biomass (Table 4) which could be a result of species-specific adaptive strategy for maximizing photosynthetic capacity across species. This finding is similar with Kaushal et al. (2022) where they reported significant differences in foliage biomass across seven bamboo species of India. However, these differences in foliage and branch biomass between the two species are unlikely to have a major impact on long-term carbon sequestration, as these components typically store less carbon than the culms. Foliage and branches are characterized by higher water content and lower lignification (Boudet 2000), which could reduce their ability to store carbon over extended periods. While differences in these components may influence short-term carbon dynamics, the culms are the primary contributors to carbon storage in bamboo due to their greater biomass accumulation

and higher lignin content (Yuen et al. 2017). Since both *B. teres* and *B. tulda* store a similar amount of biomass in their culms (i.e. higher proportion than foliage and branch), their carbon sequestration potential in the long term is likely to be comparable. This aligns with Kaushal et al. (2022) which reported no significant difference in culm biomass across *Bambusa* species. As the culm biomass plays a dominant role in carbon storage, and both species are expected to sequester similar amounts of carbon over their lifespan. The analysis of green weight fraction further underscores species-specific allocation strategies (Fig. 2). *B. teres* allocates more green biomass to the culm than *B. tulda*, making it better suited for timber production due to its stronger, more durable culms. In contrast, *B. tulda* invests more biomass in branches and foliage than *B. teres*, which is beneficial for fodder and other uses like mulching or green manure. For

a farmer looking to maximize timber production, *B. teres* would be the better choice due to its higher culm biomass. However, if the farmer is more focused on fodder for livestock or wants to integrate bamboo into an agroforestry system, *B. tulda* would be more suitable due to its greater biomass allocation to branches and foliage.

Allometric models for biomass estimation of *B. teres* and *B. tulda*

Our results support the initial hypothesis, showing that models incorporating both DBH and height provide better predictive accuracy. Models M3, M6, M9, and M12 consistently outperformed those using only DBH or height, achieving adjusted R^2 values above 0.8 for culm and total AGB biomass (Tables 5 and 6). These findings align with studies from bamboo forests such as Tesema et al. (2024) on *Oxytenanthera abyssinica* in Northwestern Ethiopia, Huy et al. (2019) on *B. procera* in Vietnam, and Kaushal et al. (2016) on *D. strictus* in India, and Kaushal et al. (2022) on seven bamboo species (*B. balcooa*, *B. bambos*, *B. nutans*, *B. vulgaris*, *D. hamiltonii*, *D. stocksii*, *D. strictus*) in India. This could be because these variables together capture more structural information about bamboo biomass. Several studies, such as Abebe et al. (2023) in Southern Ethiopia, Xayalath et al. (2019) in Northern Laos, Yuen et al. (2017) in Thailand, and Puangchit et al. (2019) in Myanmar, have developed allometric models using only DBH. This approach was chosen in those studies because the difference in predictive accuracy between models using DBH alone and those incorporating both DBH and height was generally small, and DBH is easier to measure in the field, making it more practical for large-scale assessments. However, in our model, the difference in accuracy was substantial, prompting us to include both DBH and height to improve predictive performance. Thus, we emphasize prioritizing model accuracy over measurement simplicity when developing allometric models for bamboo biomass estimation, recognizing that the optimal approach may vary across species and environmental conditions.

In terms of model form, the power model performed better for culm biomass and total AGB estimation in both *B. teres* and *B. tulda* (Tables 5

and 6). This aligns with the findings from previous studies (Kaushal et al. 2016, 2022; Huy et al. 2019; Xayalath et al. 2019; Yuen et al. 2017; Abebe et al. 2023; Tesema et al. 2024) from different countries for different bamboo species. Bamboo exhibits rapid early growth, followed by a slower accumulation of biomass as it matures (Tao et al. 2020). This non-linear growth pattern makes power functions well-suited for modeling biomass estimation, as they can effectively capture these changes compared to simple linear models. Additionally, many biological processes follow allometric scaling, where size-related traits, such as DBH and height, scale in a manner that is proportional or follows a power-law relationship, rather than in a linear fashion. The cross-validation results of the fitted allometric models demonstrated a strong fit, high predictive accuracy, and minimal prediction error, as indicated by low bias and RMSE values (Tables 5 and 6). Furthermore, residual plots for culm biomass and AGB suggest that models satisfied the assumption of normality due to the distribution of residuals, and the residual errors did not show any consistent pattern against the predicted values, indicating the model's strength (Fig. 4). We suggest using power form of regression model to develop biomass allometric models for culm and total AGB for different bamboo species outside forest area in Nepal.

However, when it comes to predicting foliage and branch biomass, the performance of the models was notably poorer (Tables 6 and 7). Even though DBH alone was the best predictor for foliage biomass in *B. teres* and branch biomass in both species, the overall predictive accuracy of these models (adjusted $R^2 < 0.53$) was unsatisfactory. This could be because the branch and foliage biomass are influenced by different variables such as environmental conditions, light availability, number of branches, crown morphology and spatial arrangement of bamboo clumps (Xayalath et al. 2019). Bamboo outside the forest area with isolated clump distribution might also affect the allocation of biomass in these components, leading to further complexity. This finding is consistent with Xayalath et al. (2019), who have suggested that the complexities involved in predicting branch and foliage biomass may render allometric models less reliable for these components. Similarly, Zhou et al. (2012) reported poor predictive performance

($R^2 < 0.40$) when estimating branch and foliage biomass of *D. vario-striata* using DBH in linear, power, and exponential models. They also concluded that this approach is not suitable for accurately predicting these biomass components. Furthermore, some studies have even excluded these components while developing allometric models due to their lower contribution to overall aboveground biomass (Tesema et al. 2024; Kaushal et al. 2022). Therefore, given the challenges in accurately predicting branch and foliage biomass using allometric models, an alternative approach could be the use of biomass ratios, which may provide a more accessible and practical solution. Since the collection of detailed branch and foliage data (e.g., leaf area index, branch length, and diameter) is labor-intensive and complex, biomass ratios might offer a simpler yet reliable estimation method. Therefore, we recommend using biomass ratios instead of allometric models for estimating foliage and branch biomass.

Species-specific allometric models are crucial for improving the accuracy of biomass estimation, as different bamboo species exhibit distinct morphological and physiological characteristics that influence biomass accumulation and allocation (Kaushal et al. 2022). In this study, Table 7 revealed that species-specific models significantly outperformed a common model in predicting culm biomass and total aboveground biomass, as evidenced by a reduction in residual sums of squares ($p < 0.01$). These results affirm that using a generalized model may introduce substantial errors when applied across species with differing growth patterns and biomass allocation strategies. Similar findings have been reported by Tesema et al. (2024) and Abebe et al. (2023), who developed species-specific models for bamboo in Ethiopia and observed notably higher prediction accuracy compared to generalized models. Kaushal et al. (2022) also emphasized considerable interspecies variability in biomass among seven Indian bamboo species and recommended species-specific models for improved estimation. Furthermore, Yuen et al. (2017) demonstrated that applying genus-level models across different site conditions led to significant prediction errors. Collectively, these studies support the necessity of developing species-specific allometric models for accurate biomass and carbon stock estimation, especially in non-forest and unmanaged bamboo landscapes like those found in Nepal.

Comparison with previously developed bamboo allometric models

We compared allometric models developed in this study specifically for bamboo outside the forest area with existing models for other land use (Tables 8 and 9). The results of this study highlight the effectiveness of species-specific and site-specific allometric models in predicting bamboo biomass. For instance, biomass models developed for total AGB estimation for *B. teres* outside forest area exhibited greater accuracy compared to previously developed genus-level equation by Yuen et al. (2017) in controlled setting. This suggests that generalized equations developed for one site may not adequately capture species-specific variations in biomass allocation. Furthermore, other species-specific models such as Puangchit et al. (2019) for *B. tulda* also performed less accurately than models developed this study. This suggests that even species-specific models may not represent accurately under different site conditions. In the context of Nepal, where bamboo is often found in scattered distributions with limited management practices, the development of species-specific allometric models becomes even more crucial. Bamboo in such areas can vary greatly in terms of growth patterns, biomass allocation, and overall productivity. Ayer et al. (2024) used equations developed by Yuen et al. (2017) for estimating aboveground biomass which might not be accurate. From t-test, we observed significant difference in biomass when Yuen et al. (2017) equation was used. However, they might have used such equation in absence of allometric models for bamboos outside forest area in Nepal. Therefore, we now suggest using equations developed in this study for bamboo biomass estimation for culm and total AGB for studies species. As we expected, existing foliage and branch biomass models also revealed significant errors (Table 8), underscoring the challenges of estimating these biomass components for bamboo, regardless of land use, when relying solely on DBH and height.

Conclusions

This study presents the first attempt to develop allometric models for estimating aboveground biomass of *Bambusa teres* and *Bambusa tulda* outside forest areas in Nepal. Although both species

stored similar total aboveground biomass, biomass allocation differed, following the same pattern: culm > branch > foliage. Among the tested models, DBH and height in combination were the best predictors for culm and total aboveground biomass, with power models performing well. However, model accuracy was lower for foliage and branch biomass, indicating that culm and total biomass equations are more reliable for biomass estimation in these species. Our study confirms the need for site- and species-specific allometric models for biomass estimation, supported by comparisons with models from different land uses. Future research should develop age-specific and belowground biomass models across more species to improve the accuracy of carbon stock assessments. The developed equations can help establish a carbon stock database in Nepal, supporting sustainable forest management and enabling participation in the global carbon credit market.

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Code availability Not applicable.

Declarations

Conflicts of interests The authors declare no competing interests.

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Consent for publication Not applicable.

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