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RESEARCH ARTICLE

Evaluation of generic allometric models for the estimation of above-ground biomass in the Indian bamboo species

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Abstract: Understanding forest productivity, carbon sequestration potential and the development of greenhouse gas inventories depends on accurate above-ground biomass measurements. Because of the limited availability of species-specific biomass estimation models, stakeholders are often compelled to use generic models. The present study critically assesses the performance of species-specific versus generic allometic equations for estimating above-ground biomass of selected bamboo species by validating model predictions against destructively measured values. The species used in the study were *Bambusa vulgaris*, *Dendrocalamus asper, Dendrocalamus giganteus, Bambusa bambos, Bambusa balcooa, Dendrocalamus strictus, Bambusa nutans* and *Dendrocalamus stocksii*. The relative error between the predicted and measured biomass for each species was calculated to assess the accuracy of the generic allometric models. Willmott's Index of Agreement was utilised to assess the variation between the estimated and measured biomass values. The results showed that species-specific equations give more accurate estimates of bamboo biomass, with consistently low relative errors. The findings clearly show that biomass models created at the species level, which integrate both diameter and height as predictive variables, yield more precise and reliable predictions.

Keywords: Bamboo biomass, Allometric equations, Biomass estimation

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Intoduction

Natural bamboo forests are high-value ecosystems that exert influence both locally and globally and offer ecological and economic advantages (Wu *et al.*, 2025). In addition to providing a range of goods for forest ecosystem functions and economies in tropical regions, bamboo also aids in the battle against poverty and climate change mitigation (Paudyal *et al.*, 2022). Bamboo is extensively distributed in the tropics and subtropics of Africa, Asia and Latin America. It has rapid expansion capability and possesses great potential for natural regeneration (Li and Kobayashi, 2004; Sawarkar *et al.*, 2025). Asia is home to almost 65% of the world's bamboo resources, with more than 1200 species distributed throughout tropical and subtropical areas. After China, India possesses a wealth of genetic variation in bamboo. More than 25% of the world's bamboo species are found in India, and are extensively scattered across all states (Tewari *et al.*, 2019).

Although allometric equations for calculating forest biomass have been developed for different geographic locations, they primarily concentrate on large tree species. There are not many biomass estimation models for bamboos, even though bamboo forests constituting a distinct forest ecosystem with significant carbon sequestration potential (Kabir *et al.*, 2023; Shivanna, 2022). Current guidelines issued by the Intergovernmental Panel on Climate Change (IPCC) do not address bamboo forests, and greenhouse gas emission reports lack standards for carbon and biomass inventories (Mukherj, 2023). Estimating biomass is crucial for figuring out the quantity and condition of biological components within an ecosystem as well as for comprehending its dynamics (Zhou *et al.*, 2023;Vashum and Jayakumar, 2012; Schroeder *et al.*, 1997).

Accurate and non-destructive assessment of carbon storage and biomass requires precise allometric equations for tree biomass estimation. However, the principles of allometric scaling for bamboo biomass estimation have not been explored much (Garcia *et al*., 2024,; Devi *et al*., 2023). Since bamboos are monocotyledonous, models designed to calculate the biomass of dicotyledonous plants are likely to produce unreliable findings (Yen *et al*., 2010). Height (H) is an important measure of forest production and demographic structure. Therefore, height (H) and diameter (D) are often used as the two fundamental input variables in growth and biomass projection systems (Devi *et al*., 2023; Singnar *et al*., 2017).

Understanding environmental productivity, carbon sequestration potential and the development of greenhouse gas inventories depend on accurate above-ground biomass measurement (Ma *et al*., 2024). The predictability of allometric models relies entirely on their ability to represent the biological and structural traits of a species (Yang *et al*., 2023). Due to the limited availability of species-specific models, stakeholders are often compelled to choose generic models. Even though generic equations are convenient, they are often developed by pooling data from multiple species and locations. As a result, there is a high risk of neglecting species-specific variations in morphology, biomass distribution, and structural characteristics. This issue is significant for bamboos as it has a great difference in culm height, inter-node space and wall thickness among species. Despite these concerns, evaluations comparing destructively measured biomass with estimates from species-specific and generic models is minimal, particularly in the Indian context. Therefore, the present study critically assesses the performance of species-specific versus generic allometric models for predicting above-ground biomass of selected bamboo species by validating model predictions against destructively measured values.

Methodology

Study area and species selected

The study was carried out at the Kerala Forest Research Institute's (KFRI) Field Research Centre (FRC) at Velupadam, Kerala. The FRC, Velupadam, is located in the Thrissur district of Kerala and represents a managed forest research landscape that supports experimental plantations and germplasm collections of economically essential bamboo species. The area has a humid tropical climate essential bamboo species. The area has a humid tropical climate and experiences both the southwest and northeast monsoon seasons. The soil is lateritic to forest type, which supports bamboo growth. Eight dominant and commercially important bamboo species were selected for the present study, namely *Bambusa vulgaris, Dendrocalamus asper, Dendrocalamus giganteus, Bambusa bambos, Bambusa balcooa, Dendrocalamus strictus, Bambusa nutans* and *Dendrocalamus stocksii.* Together, these species represent a range of culm structures, diameters, heights and other structural traits commonly found in tropical bamboo ecosystems.

Bamboo harvesting and biomass estimation

Sampling was conducted using a stratified design, in which each bamboo species constituted a separate stratum. This method was adopted due to field constraints and differences in species abundance. The number of culms samples in each species for the estimation is given in Table 1. Fallen and harvested culms were utilised to assess DBH (diameter at breast height), height and weight. Representative culm samples from each species were oven-dried at 80ºC for 72 hours to calculate the dry weight to fresh weight ratio. Summary statistics for the biometric measurements were prepared (Table 1).

The accuracy of the generic allometric equations put forward by Kigomo *et al*., (2025) and Xayalath *et al*., (2019) was evaluated by calculating the relative error between the predicted and measured biomass for each species. These generic allometric models put forward by Kigomo *et al*., (2025) and Xayalath *et al*., (2019) (Table 2) were chosen because they were developed using bamboo species common to tropical regions, including species present in our study area, and were explicitly proposed by the authors for application across a wide range of bamboo species in tropical areas. Species-specific allometric models for the studied bamboo species were compiled from previous studies and applied to estimate biomass (Table 3).

The relative error (RE) for above-ground biomass (AB) estimation was worked out using the equation.

$$RE = \frac{(\boldsymbol{AB\ predicted - AB\ measured})}{\boldsymbol{AB\ measured}} \text{ ------- Eq-1}$$

The accuracy of the models was assessed using relative error (%) and overall bias. At the same time, goodness of fit was further evaluated through observed-versus-predicted scatter plots and the corresponding coefficient of determination (R^2). Index of agreement (d) put forward by Willmott (1981) was utilised to assess the difference between the predicted (E) and the measured

Table 1. Summary statistics of different above ground parameters. Min: Minimum value and Max: Maximum value; mean ± SE value within biometric parameter

Species (sample size)	Sumary Statistics	Culm diameter (cm)	Culm height (m)	Culm weight (kg) Species-specific equation	Culm weight (kg) Generic Equation Model 1	Culm weight (kg) Generic Equation Model 2	Culm weight (kg) Destructive method
Bambusa vulgaris (26)	mean±SD	4.15±0.13	9.5±0.78	3.1±0.05	4.3±0.08	4.22±0.06	3.312±0.20
	MIN	3.1	3	2.5	3.6	3.6	2.8
	MAX	5.2	16	3.4	5	4.23	3.324
Dendrocalamus asper (21)	mean±SD	6.3±0.55	9.8±0.18	8.9±0.17	7.8±0.16	10.7±0.21	9.35±0.18
	MIN	5.42	8.52	7.5	6.5	9.2	8
	MAX	7.23	11.23	10.3	9.1	12.2	10.7
Dendrocalamus giganteus (18)	mean±SD	10.02±0.5	10.59±0.21	17.49±0.38	15.4±0.30	30.2±0.62	18.52±0.37
	MIN	7.43	9.5	14.8	13.2	25.6	15.8
	MAX	12.52	11.41	20.18	17.6	34.8	21.24
Bambusa balcooa (22)	mean±SD	5.96±0.18	9.98±0.48	16.3±0.30	7.3±0.18	9.4±0.20	15.65±0.28
	MIN	4.5	6.2	13.8	5.8	7.8	13.2
	MAX	7.2	13.5	18.8	8.8	11	18.1
Bambusa bambos (24)	mean±SD	7.64±0.53	10.03±0.91	22.5±0.48	10.3±0.26	16.5±0.36	24.23±0.47
	MIN	3	1.5	18	8	13.2	19.8
	MAX	11.18	17.45	27	12.6	19.8	28.66
Dendrocalamus strictus (23)	mean±SD	5.58±0.41	8.17±0.60	9.95±0.23	5.8±0.16	8.2±0.18	10.52±0.22
	MIN	2.3	3	7.8	4.3	6.5	8.4
	MAX	8.5	12.4	12.1	7.3	9.9	12.64
Bambusa nutans (20)	mean±SD	5.63±0.46	9.92±0.85	16.9±0.32	6.7±0.17	8.3±0.18	15.65±0.28
	MIN	2.1	3	14.2	5.2	6.8	13.15
	MAX	8.9	15	19.6	8.2	9.8	18.45
Dendrocalamus stocksii (28)	mean±SD	3.53±0.22	7.15±0.62	4.9±0.11	2.8±0.07	2.9±0.07	5.12±0.11
	MIN	1.6	1.3	3.8	2.1	2.2	4.1
	MAX	5.5	12	6	3.5	3.6	6.14

Table 2. Evaluated generic models for estimating the above-ground biomass of bamboo species

Model code	Allometric models	Source
Model 1	$AB = 0.123 \times (H \times DBH^2)^{0.696}$	Kigomo *et al., 2025*
Model 2	$AB = 0.179 \times DBH^{2.221}$	Xayalath *et al., 2019*

Table 3. Species-specific allometric equations used for biomass estimation

Species	Equations	References
Bambusa nutans	$AB = 0.16 \times D^{2.34} \times H^{0.27}$	Kaushal *et al.,* 2022
Bambusa balcooa	$\ln AB = 2.149 + 2.284 \ln D$	Nath *et al.,* 2009
Bambusa balcooa	$\ln AB = 2.199 + 2.353 \ln D$	
Bambusa balcooa	$\ln AB = 2.368 + 2.214 \ln D$	
Bambusa balcooa	$\ln AB = 2.153 + 2.477 \ln D$	
Dendrocalamus stocksii	$AB = 0.30 \times (D^2H)^{0.62}$	Kaushal *et al.,* 2022
Bambusa bamboos	$AB = 0.35 \times D^{2.04}$	Kaushal *et al.,* 2022
Dendrocalamus strictus	$AB = 0.11 \times D^{1.92} \times H^{0.57}$	Kaushal *et al.,* 2022
Dendrocalamus asper	$AB = 0.0876 \times DBH^{1.342} \times H^{0.943}$	Kigomo *et al.,* 2025
Dendrocalamus giganteus	$AB = -2.286 + 0.197 \times DBH^2$	Kigomo *et al.,* 2025
Bambusa vulgaris	$AB = 0.1867 \times DBH^{2.627} \times H^{-0.416}$	Kigomo *et al.,* 2025

biomass values (O) (Equation 2). The index ranges from 0 to 1, where better agreement is indicated by values nearer to 1.

$$d = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}(|E_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad \text{----Eq-2}$$

E_i = Predicted (estimated) value
O_i = Observed value
$\bar{O}$ = Mean of observed values
n = Number of observations

Scatter plots of observed versus predicted biomass were developed for model 1, model 2 and the species-specific model. A linear regression trend line was fitted to each dataset and the corresponding R^2 value was displayed to evaluate model performance.

Result and discussion

The results show that across all eight bamboo species, the species-specific equations consistently yielded the lowest relative errors, ranging from −7.14% to +7.99%. This indicates minimal bias and high accuracy in biomass estimation when species-specific allometric equations are used. In contrast, Model 1 showed higher relative errors, mostly negative, indicating a tendency to underestimate biomass. The relative error values for Model 1 ranged from −16.58% to −57.49%, except for *Bambusa vulgaris*, which showed a positive error of 29.83%, indicating overestimation. The large error magnitudes across all species suggest that Model 1 is not reliable for multi-species bamboo biomass estimation. Similarly, Model 2 also showed significant deviations from the observed biomass, with relative errors ranging from −46.96% to +63.07%. Although Model 2 performed marginally better than Model 1 for a few species (e.g., *Bambusa bambos* and *Dendrocalamus strictus*), it still showed over- or underestimation. In particular, the high positive error for *Dendrocalamus giganteus* (+63.07%) indicates poor model generalizability.

Together, the comparative analysis clearly indicates that species-specific allometric models give the most precise estimates of bamboo biomass, with consistently low relative errors. In contrast, both generalised models (Table 4) showed high relative error percentage and significant inter-species variability, making them less suitable for accurate biomass estimation across diverse bamboo species.

Willmott's Index of Agreement (d) was used to assess the performance of the different biomass estimation models (Table 5). The generic equation (Model 1) showed moderate agreement with the measured biomass (d = 0.681), indicating substantial deviations between predicted and measured biomass across species. In contrast, the generic equation (Model 2) demonstrated a substantially improved fit (d = 0.808), showing a good overall agreement and reduced prediction errors. Clear differences were exhibited among the models in

Table 4. Relative percent error of generic and species-specific equations in evaluating above-ground biomass of different bamboo species

Bamboo Species	Relative error percentage of the species-specific equation	Relative error percentage of Model 1	Relative error percentage of Model 2
Bambusa vulgaris	-6.40	29.83	27.42
Dendrocalamus asper	-4.81	-16.58	14.44
Dendrocalamus giganteus	-5.56	-16.85	63.07
Bambusa balcooa	4.15	-53.35	-39.94
Bambusa bambos	-7.14	-57.49	-31.90
Dendrocalamus strictus	-5.42	-44.87	-22.05
Bambusa nutans	7.99	-57.19	-46.96
Dendrocalamus stocksii	-4.30	-45.31	-43.36

predicting the above ground biomass. The species-specific equations (d = 0.995) exhibited the highest performance, showing near-perfect agreement with the actual above-ground biomass. This very high index value (d = 0.995) emphasizes the need to use species-specific models for each bamboo species to measure accurate biomass without destructive sampling.

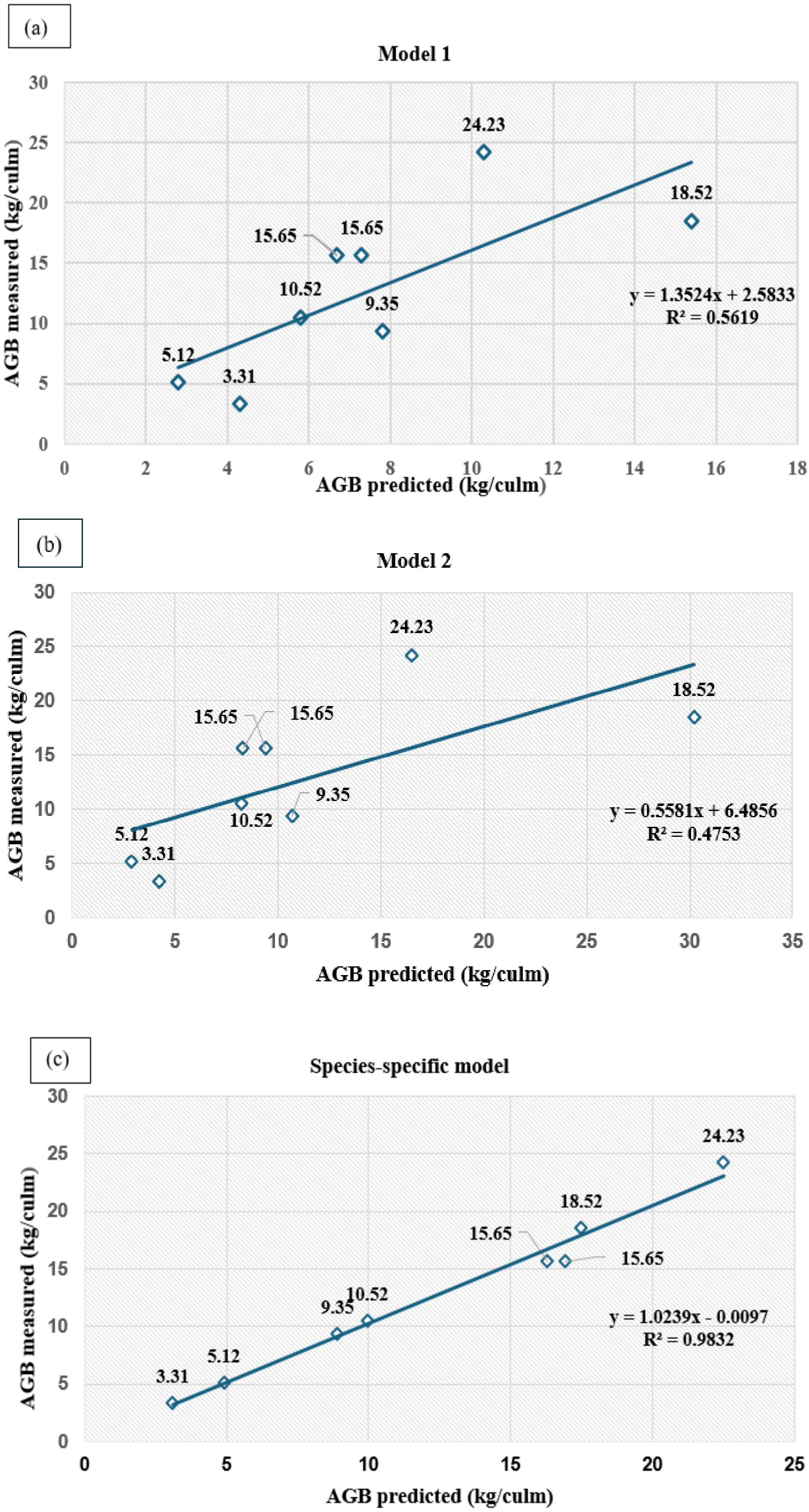
The scatter plots (Fig 1. a to c) showed apparent differences in model performance among the three biomass estimation approaches. The species-specific equation showed better alignment between measured and predicted biomass, with a high coefficient of determination ($R^2 = 0.98$). In contrast, Generic Model 1 showed greater dispersion of points around the trend line, as shown in a moderate R^2 of 0.50. Generic Model 2 showed even lower explanatory power, with greater scatter and an R^2 value of 0.40. Overall, the scatter plot analysis confirms that species-specific allometric models provide more accurate estimates than generic allometric models for bamboo biomass estimation.

Bamboos, classified as woody grasses, show vast species -level differences in DBH, culm hollow cavity and internode length, all of which strongly influence the above-ground biomass distribution (Inada, 2004). In many cases, the non-availability of species-level allometric equations compels researchers and practitioners to rely on generic equations for biomass estimation. As allometric models are based either on girth alone or on a combination of girth and height, and these variables differ greatly among bamboo species, the development of species-level allometric equations is essential for precise biomass estimation of bamboo (Kaushal *et al*., 2022). A major reason for errors while using generic models is the inappropriate representation of species-level biological and structural variability (Yang *et al*., 2023). In bamboos, internode length, wall thickness and hollow culms influence the bamboo biomass accumulations, yet these characteristics are not properly represented in generalized equations (Tan *et al*., 2024).

Table 5. Willmott's Index of Agreement (d) for different biomass estimation models evaluated against destructively measured biomass

Model	Willmott's Index of Agreement (d)	Interpretation
Model 1	0.681	Moderate agreement
Model 2	0.808	Good agreement
Species-specific equation model	0.995	Near-perfect agreement

Fig 1. Scatter plots of measured versus predicted above-ground biomass for (a) Generic model 1 (b) Generic model 2 and (c) species-specific model



Generalized equations usually incorporate mean data or datasets sourced externally, which often fails to represent the species-level conditions. Developing generic equations from limited datasets results in extrapolation errors when they are applied to structurally distinct systems. Variations in environmental factors and wood density cause either overestimation or underestimation of biomass (Xiang *et al*., 2016). Ngomanda *et al*. (2014) suggested that species-specific allometric equations are more reliable than generic equations. The use of pantropical allometric models leads to significant uncertainty in carbon stock and biomass estimation. For accurate biomass estimation, the development of species-specific biomass estimation is necessary (Daba *et al*., 2019). The absence of location-specific allometric models compelled the researchers to use the pantropical model. However, the use of pantropical generalised allometric equations can lead to errors in biomass estimation (Fayolle *et al*., 2013; Henry *et al*., 2010). The importance of developing species and location-specific allometric models for tropical forests, aiming to avoid errors arising from the use of generic pantropical models, has been confirmed by Ngomanda *et al*., (2014).

Conclusion

Ecosystem valuation is crucial for effectively engaging policymakers. Accurate measurement of above ground biomass plays an important role in this process. In bamboo ecosystems, the use of multi-species allometric equation (Model 1 and Model 2) resulted in both overestimation and underestimation of biomass. As per the present study, neither of the evaluated multi-species models can be reliably applied for accurate biomass estimation. The findings from the study indicate that allometric models developed at the species level, using both diameter and height as predictor variables, give more accurate and reliable estimates. Therefore, the development and application of species-specific allometric models are advised for better ecosystem valuation. Efforts should be made to develop species-specific allometric equations for the dominant and commercially cultivated bamboo species to ensure accurate biomass estimation.

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