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Feasibility in Estimating the Dry Leaf Mass and Specific Leaf Area of 50 Bamboo Species Based on Nondestructive Measurements

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Abstract: Specific leaf area (SLA) is a good predictor of aboveground net primary productivity. However, the SLA of bamboo species is generally estimated on the basis of destructive measurements rather than the cost-effective and recyclable nondestructive measurements using easily accessible leaf traits such as leaf length (L) and width (W). Considering the strong empirical relationships between leaf area (LA) and leaf structural parameters of bamboo species that were developed by previous studies, this study explores the feasibility of estimating the leaf dry mass (LDM) and SLA of 50 bamboo species using L and W. The results show that the Montgomery equation and its similar forms precisely estimated LA of the 50 bamboo species at both leaf scale ($R^2 > 0.96$ and $MAE\% < 4.67\%$) and the canopy scale ($R^2 > 0.99$ and RMSE < 0.09); the LDM of the 50 bamboo species could also be estimated using L and W at both leaf scale ($R^2 > 0.52$ and $MAE\% < 26.35\%$) and the canopy scale ($R^2 > 0.99$ and RMSE < 0.003), and the estimated mean SLA of each of the 50 bamboo species had good agreement with the measured values ($R^2 > 0.99$ and RMSE < 1.88) because of the precisely estimated mean LA and mean LDM at the canopy scale, indicating the feasibility of estimating SLA of the 50 bamboo species at the canopy scale based on nondestructive measurements. However, the empirical relationships used for mean SLA estimations are not suitable for SLA estimations at the leaf scale because of the uncertainties in the estimated LDM at the leaf scale.

Keywords: specific leaf area; leaf length; leaf width; empirical models; bamboo species

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1. Introduction

Bamboos are widely distributed in tropical, subtropical, warm, and temperate regions between 46° N and 47° S, which covers a total area of 31.47 million hectares, accounting for 0.78% of the global forest area [1]. In Asia, bamboos are used by 2.5 billion people for fibers or industrial materials, and as important sources of bioenergy, food products, construction materials, and a component of environment management regimes [2–4].

Specific leaf area (SLA) is defined as the ratio of leaf area (LA) and dry mass (LDM) of a leaf. As one of the primary physical characters of leaves, SLA is closely related to the growth rate, reproduction strategy, and life span of plants [5,6]. SLA is generally estimated on the basis of destructive measurements of LA and LDM [7,8], which are cost ineffective, and the same leaf cannot be repeatedly measured to produce SLA time series [9]. Regarding rare plants, destructive measurements of SLA are unacceptable. Therefore, empirical relationships are developed for rapid and nondestructive LA and LDM measurements, respectively, on the basis of structural leaf parameters (e.g., leaf length (L) and width (W)) [9–13]. However, there are few studies estimating the SLA using L and

W. The only example is the SLA estimations of five deciduous broad-leaved trees using L and W by Liu et al. [12]. Regarding bamboo species, previous studies focused on LA estimations based on L and W (Shi et al. [14]), but few addressed LDM and SLA estimations using nondestructive measurements.

The Montgomery equation is the semiempirical linear model developed for LA estimations using simple equation LA = $\alpha \cdot L \cdot W$, where α is the Montgomery parameter (Montgomery [15]). The theoretical range of α was given by Shi et al. [16] through rearranging the formula of the simplified Gielis equation (SGE) (Shi et al. [17]). Then, the validity of the Montgomery equation was proved to estimate the LA for several types of leaves, such as Magnoliaceae species (He et al. [18]). Yu et al. [19] also suggested that the Montgomery equation was a simple and effective model in the LA estimations of 15 types of lianas leaves. Apart from the Montgomery equation, other linear models can be used for LA estimations for several specific leaves, such as those of the fava bean (Peksen [20]). Power models are another popular choice for LA estimations (Antunes et al. [21]; Pompelli et al. [10]). For example, the LA values of eight genotypes of coffee trees were estimated on the basis of a power model by Antunes et al. [21]. Regarding bamboo species, the Montgomery equation showed good performance in the LA estimations of 101 bamboo species ($R^2 > 0.98$) (Shi et al. [14]).

Bidarnamani et al. [22] pioneered in estimating LDM using leaf structural parameters. They found that the LDM of *Ficus benjamina* (cv. Starlight) could be estimated using L·W because of the strong power relationship between L·W and LDM ($R^2 = 0.77$). The LDM of *Tectona grandis* was also estimated using L·W ($R^2 = 0.87$) by Tondjo et al. [11]. In addition to L and W, leaf thickness is used as an optional predictor for LDM estimations [12,23]. However, the feasibility of estimating the LDM of bamboo species on the basis of nondestructive measurements is unclear.

The goal of this study is to estimate the SLA of a total of 50 bamboo species using nondestructive methods and to contrast and validate the empirical models for the SLA estimations to find a better fit. To achieve this goal, the empirical models, to our knowledge, used for LA and LDM estimations in previous studies [10,13,16,20,24] and other possible models on the basis of L and W were employed for SLA estimations in this study. The scientific question is whether nondestructive measurements can be used for the SLA estimations of bamboo species.

2. Materials and Methods

2.1. Study Area

The study sites were located in the campus of Zhejiang A&F University (30°15′20″ N, 119°44′1″ E) and the China Bamboo Exposition Park (30°35′40″ N, 119°39′30″ E), southeastern China. Both the two study sites have flat terrain, with elevation ranging from 30 to 50 m. The study sites were in the subtropical monsoon climate zone, with an average annual precipitation of 1614 mm and a mean temperature of 15.9–17.0 °C. The annual sunshine hours are about 1800 h. The primary soil types are Ferralsols (according to the FAO soil classification system).

2.2. Data Collection

The healthy and mature leaves of a total of 50 bamboo species were sampled in the two sites in November 2020 (Table 1). The names of the 50 bamboo species were obtained from labels of the bamboos provided by the managers of the two study sites. Most names of the 50 bamboo species can be found on the website of the World Checklist of Selected Plant Families [25]. According to the crown sizes of the 50 bamboo species, three sampling strategies were followed: (1) Crowns were evenly divided into the upper, middle, and lower parts for crown height no less than 2 m, and at least 50 leaves were randomly sampled from more than 10 crowns for each of the 3 parts; (2) if a crown's height was between 1 and 2 m, the crown was evenly divided into upper and lower parts, and at least 60 leaves were randomly sampled from more than 10 crowns for each of the 2 parts;

(3) at least 100 leaves were randomly sampled from more than 20 crowns without height partition for crown heights of less than 1 m.

Table 1. Details of sampled leaves of 50 bamboo species. Crowns were evenly divided into upper, middle, and lower parts for crown height no less than 2 m. If a crown's height was between 1 and 2 m, the crown was evenly divided into upper and lower parts. Height partition was not considered for crown heights of less than 1 m. Leaves of the 50 bamboo species were fewer than the initial number of samples because low-quality scanned images were discarded, such as those of the folded or overlapped leaves.

No.	Bamboo Species	Number of Leaves		
		Upper	Middle	Lower
1	*Shibataea chinensis* Nakai		100 leaves without height partitions	
2	*Shibataea nanpingensis* Q. F. Zheng & K. F. Huang		93 leaves without height partitions	
3	*Pseudosasa cantorii* (Munro) Keng f. in Y.L.Keng		91 leaves without height partitions	
4	*Phyllostachys nidularia* f. *vexillaris* Wen	59	-	60
5	*Oligostachyum spongiosum* (C. D. Chu & C. S. Chao) G. H. Ye & Y. P. Wang	60	-	59
6	*Phyllostachys longiciliata* G. H. Lai	58	-	57
7	*Pleioblastus amarus* var. *hangzhouensis* S. L. Chen & S. Y. Chen	59	-	58
8	*Phyllostachys rubicunda* T. W. Wen	60	-	53
9	*Phyllostachys nidularia* Munro	60	-	57
10	*Indosasa levigata* Z. P. Wang et G. H. Ye	55	-	59
11	*Phyllostachys platyglossa* Z. P. Wang & Z. H. Yu	57	-	57
12	*Pseudosasa japonica* 'Tsutsumiana'	59	-	60
13	*Phyllostachys aurita* J. L. Lu	51	-	57
14	*Phyllostachys meyeri* McClure	60	-	55
15	*Phyllostachys hispida* S. C. Li	55	-	59
16	*Pseudosasa japonica* f. *akebonosuji*	55	-	59
17	*Oligostachyum lubricum* (Wen) Keng f.	57	-	60
18	*Acidosasa chinensis* C. D. Chu et C. S. Chao	52	-	60
19	*Phyllostachys tianmuensis* Z. P. Wang & N. X. Ma	59	-	59
20	*Phyllostachys atrovaginata* C. S. Chao & H. Y. Chou	60	-	59
21	*Bambusa multiplex* 'Alphonso-Karrii' R. A. Young	56	-	51
22	*Phyllostachys robustiramea* S. Y. Chen & C. Y. Yao	53	-	55
23	*Sinobambusa yixingensis* C. S. Chao & K. S. Xiao	54	-	60
24	*Phyllostachys zhejiangensis* G. H. Lai	55	-	59
25	*Phyllostachys platyglossa* Z. P. Wang et Z. H. Yu	59	-	58
26	*Phyllostachys parvifolia* C. D. Chu & H. Y. Chou	50	39	48
27	*Bambusa multiplex 'Willowy'* R. A. Young	46	48	48
28	*Pleioblastus maculatus* (McClure) C. D. Chu & C. S. Chao	50	50	46
29	*Chimonobambusa unifolia* (T. P. Yi) T. H. Wen in D. Ohrnberger	50	50	49
30	*Pseudosasa amabilis* (McClure) Keng f. in Y. L. Keng	47	48	50
31	*Indosasa gigantea* (T. H. Wen) T. H. Wen	44	50	45
32	*Phyllostachys edulis* 'Heterocycla'	50	50	48
33	*Phyllostachys edulis* 'Tao kiang'	44	45	44
34	*Sinobambusa tootsik* f. *luteoloalbostriata* (S. H. Chen & Z. Z. Wang) T. P. Yi	48	48	46
35	*Phyllostachys aureosulcata* McClure	50	50	50
36	*Phyllostachys aureosulcata* 'Aureocaulis' Z. P. Wang et N. X. Ma	50	50	49
37	*Phyllostachys vivax* 'Aureocaulis' N. X. Ma	50	50	50
38	*Acidosasa edulis* (T. H. Wen) T. H. Wen	49	50	50
39	*Phyllostachys aureosulcata* f. *flavostriata*	44	49	49
40	*Phyllostachys aureosulcata* 'Spectabilis'	50	50	48
41	*Pleioblastus amarus* (Keng) Keng f.	50	46	50
42	*Pleioblastus ovatoauritas* Wen	45	46	48
43	*Sinobambusa intermedia* McClure	48	50	50
44	*Phyllostachys sulphurea* 'Houzeau' McClure	45	48	49
45	*Phyllostachys vivax f. viridivittata*	50	50	50
46	*Sinobambusa tootsik* var. *laeta* (Mcclure) Wen	50	49	50
47	*Pleioblastus gozadakensis* Nakai	49	50	50
48	*Sinobambusa tootsik* (Makino) Makino ex Nakai	49	48	45
49	*Pleioblastus chino* var. *hisauchii* Makino	49	50	49
50	*Bambusa multiplex* (Lour.) Raeusch. ex Schult.	48	47	45

Sampled leaves were quickly scanned using an Epson perfection V30 SE scanner (Seiko Epson Corporation, Nagano, Japan) to avoid leaf deformation caused by water loss. Scanned images were classified as leaves and background for L, W, and LA estimations using MATLAB 2014a software based on digital image processing techniques (Table A1). L is defined as the distance from the leaf apex to the junction of the lamina and petiole of a leaf, and W is defined as the longest distance of the leaf perpendicular to L (Figure 1). All sampled leaves of the 50 bamboo species were separately packed in paper bags and oven-dried at 80 °C for 48 h until their dry weight was constant. Then, the dry mass of sampled leaves was measured using an electronic balance (Wuxin Weighing Apparatus Co., Ltd., Zhejiang, China) with an accuracy of 0.0001 g (Table A1). However, the sampled leaves of some sections were fewer than the initial number of samples because low-quality scanned images were discarded, such as those of folded or overlapped leaves (Table 1).

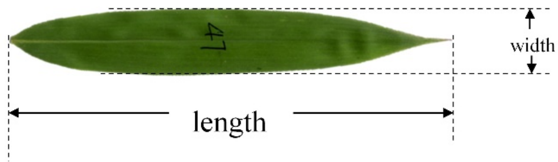

Figure 1. Example of length and width of bamboo leaves.

2.3. Methods

The averaged SLAs for each of the 50 bamboo species were estimated as follows:

$$\overline{\mathrm{SLA}} = \frac{1}{n}\sum_{i=1}^{n}\mathrm{SLA}_i = \frac{1}{n}\sum_{i=1}^{n}\frac{\mathrm{LA}_i}{\mathrm{LDM}_i} \tag{1}$$

where LA_i, LDM_i, and SLA_i are the area, dry mass, and SLA of the *i*th leaf of a specific bamboo species; n is the number of the sampled leaves used for developing or evaluating empirical models of $\overline{\mathrm{SLA}}$ estimations. The linear models, including the Montgomery equation, and the power models were used for modeling LA and LDM, respectively (Table 2). In this study, 75% of the total leaves of a bamboo species were randomly selected to develop the models, and the remaining 25% of leaves were used for evaluating the performance of the developed models. In order to quantify the effects of sampling difference on the development of the models, each one of the models was developed and validated 40 times on the basis of varying training and validation samples, respectively.

Table 2. Models for LA and LDM estimations. The models used by previous studies and other possible models on the basis of L and W were employed in this study [13,16,20].

Model Types	Models	Equations	Leaf Area (LA)	Leaf Dry Mass (LDM)
Linear models	A	$y = a \cdot L + b$	√	√
	B	$y = a \cdot W + b$	√	√
	C	$y = \alpha \cdot L \cdot W$	√	-
	D	$y = a \cdot L \cdot W + b$	√	√
	E	$y = a \cdot L/W + b$	√	√
Power models	F	$y = a \cdot L^{b}$	√	√
	G	$y = a \cdot W^{b}$	√	√
	H	$y = a \cdot (L \cdot W)^{b}$	√	√
	I	$y = a \cdot (L/W)^{b}$	√	√
	J	$y = a \cdot L^{b} \cdot W^{c}$	-	√

Note: y represents LA and LDM for leaf area and leaf dry mass estimations, respectively; a, b and c are equation parameters; and Model 3 is the Montgomery equation.

The Akaike information criterion (AIC) was used for selecting the suitable models in LA and LDM estimations [23,26].

$$\mathrm{AIC} = 2\mathrm{K} + n\left[\ln 2\pi\frac{\sum_{i=1}^{n}(\mathrm{T}_i - \mathrm{P}_i)^2}{n} + 1\right] \tag{2}$$

where K is the number of parameters of the model; *n* is the number of leaves; T_i is the measured value of LA or LDM of the *i*th leaf; P_i is the estimated value of LA or LDM of the *i*th leaf. The AIC value deals with the trade-off between the goodness of fit and simplicity of the model. Given the set of candidate models for SLA estimations of bamboo leaves, the preferred model was the one with the minimal AIC value.

The determination coefficient (R^2), root mean squared error (RMSE), and the mean absolute error percentage ($MAE\%$) were used for evaluating the performance of the developed models [12,27].

$$MAE\% = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \times 100\% \tag{3}$$

where y_i and $\hat{y}_i$ are the measured and estimated values of the ith sample, respectively.

3. Results and Discussion

3.1. Model Selection

In this study, AIC values were largely determined by the goodness of fit of the models (second term of the right-hand side of Equation (2)) for LA and LDM estimations, rather than the simplicity of the models (first term of the right-hand side of Equation (2)). According to the AIC of the models, Models C, D, and H achieved relatively better performance than that of the six other models for LA estimations (Figure 2) and were used as the numerator of Equation (1). Models D, H, and J were selected from the nine models of LDM estimations in Table 2 as the denominator of Equation (1) (Figure 2). Therefore, a total of nine models could be developed for $\overline{\text{SLA}}$ estimations by combining each of the three models of LA estimations and each of the three models of LDM estimations.

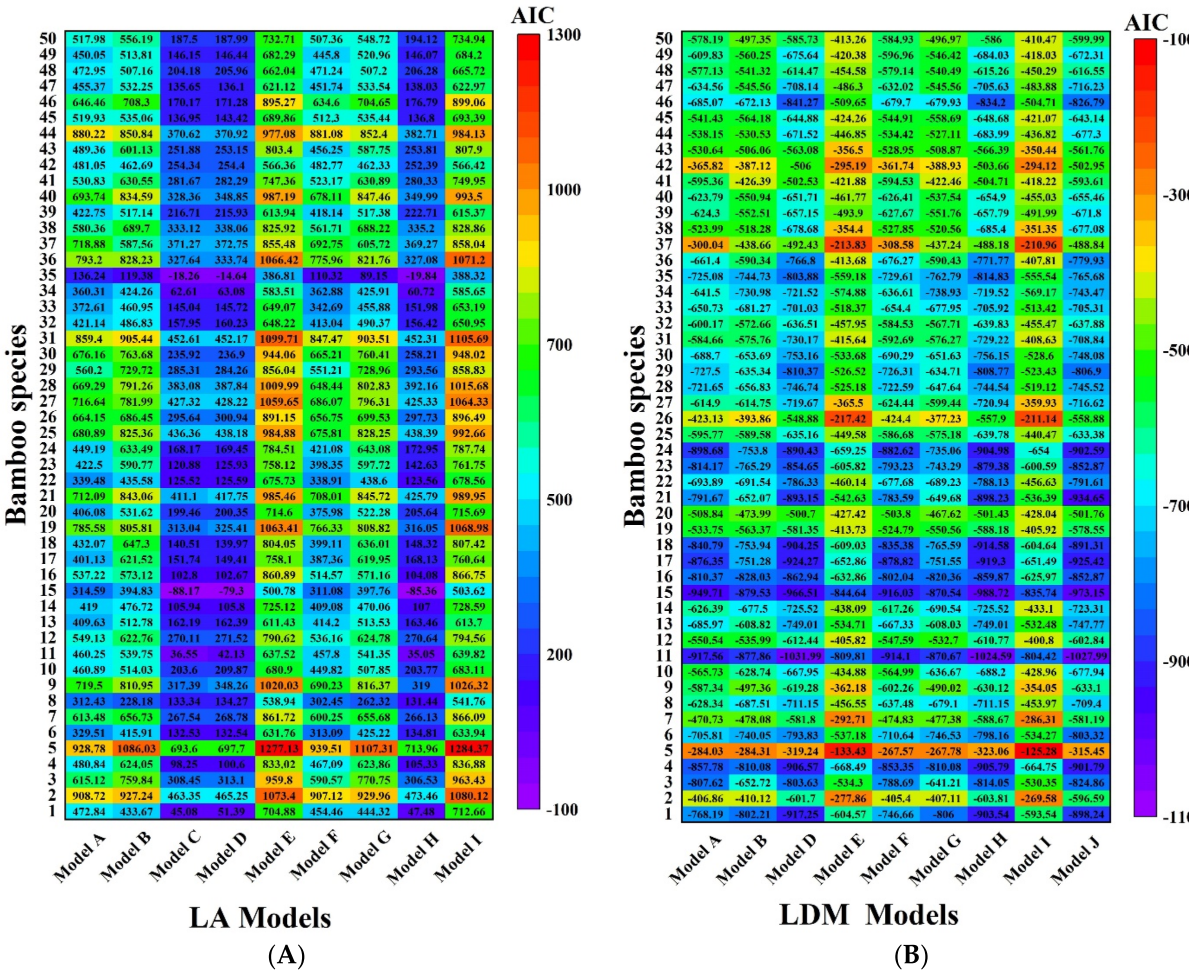

Figure 2. Comparison of AIC values calculated for different models for LA (**A**) and LDM (**B**) estimations of 50 bamboo species.

3.2. Models for Leaf Area Estimations

In this study, parameter a of Models D and H was close to the α of the Montgomery equation (Model C), parameter b of Model D was close to 0, and parameter b of Model

H was close to 1. Therefore, the difference in the performance of the three models for LA estimations was minor at both the leaf scale (Figure A1) and the canopy scale (Figure A2) and as good as in previous studies [10,14,19].

The Montgomery equation was one of the best models used for LA estimations in this study. Shi et al. [16] derived the theoretical values of the Montgomery parameter (α) ranging from 1/2 to $\pi/4$. Regarding the linear leaf shape, especially for Poaceae plants, the values of α were narrowed to the range from 0.6795 to $\pi/4$ on the basis of the SGE model by Shi et al. [17]. The validity of the range of α was proven by Shi et al. [16] for typical leaves with elliptical, sectorial, linear, and triangular shapes. In this study, there were 4 α of the 50 bamboo species that were not located within the range of α of the linear leaf shape, and only 2 α slightly higher than the theoretical values of α (Figure 3). The α was derived on the basis of regular geometric shapes that were the abstraction of unregular leaves. Therefore, the theoretical range of α may not fully cover the estimated values of α (Lin et al. [28]).

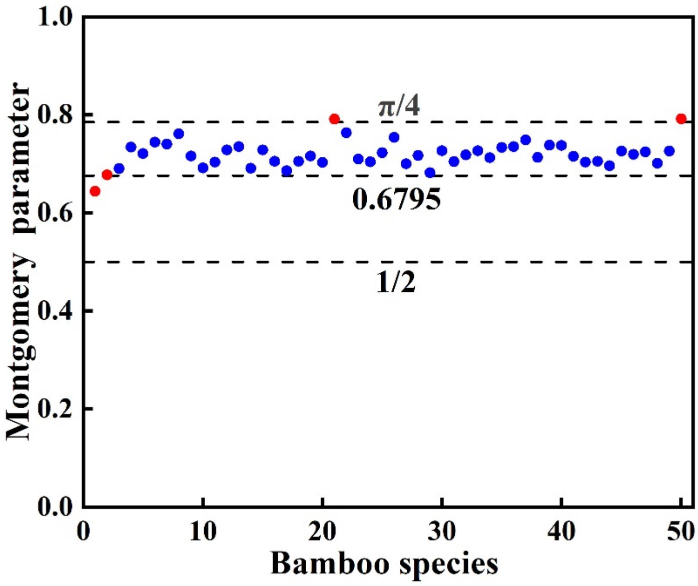

Figure 3. Montgomery parameter (α) of 50 bamboo species. The theoretical value of α ranged from 1/2 to $\pi/4$, and the theoretical value of α of Poaceae plants ranged from 0.6795 to $\pi/4$.

Regarding LA estimations, previous studies indicated that the performance of the two-variable model (L and W) was better than that of the one-variable models (L or W) [12,14,20]. All three selected models for estimating LA use L·W rather than other variables or combinations, such as L, W, and L/W. Leaf shape can generally be considered invariant for a specific tree species because genetics strongly controls cell multiplication in some defined meristem zones and thereby determines leaf shape [12,29]. In addition, L and W determine the LA for the specific leaf shape. Therefore, LA being proportional to L·W is reasonable and supported by other leaf species, such as *Jatropha curcas*, *Tectona grandis*, and *Ficus benjamina* (cv. Starlight) [10,11,22].

3.3. Models for Leaf Dry Mass Estimations

Although the performance of the three selected models for LDM estimations at leaf scale was not as good as that of models used for LA estimations (Figure A3), correlations between the measured and estimated mean LDM ($\overline{\text{LDM}}$) were strong (Figure A4). The discrepancy between the measured and estimated LDM at leaf scale was because LDM variation of a bamboo species was not only determined by L and W, but it also depended on the density of the dry matter of a specific leaf, which is determined by its living environment [7,30,31]. The errors of estimated LDMs cancel each other out in the average processes of $\overline{\text{LDM}}$ calculations because of the nearly symmetrical distributions of errors of the estimated LDM of the 50 bamboo species (Figure 4).

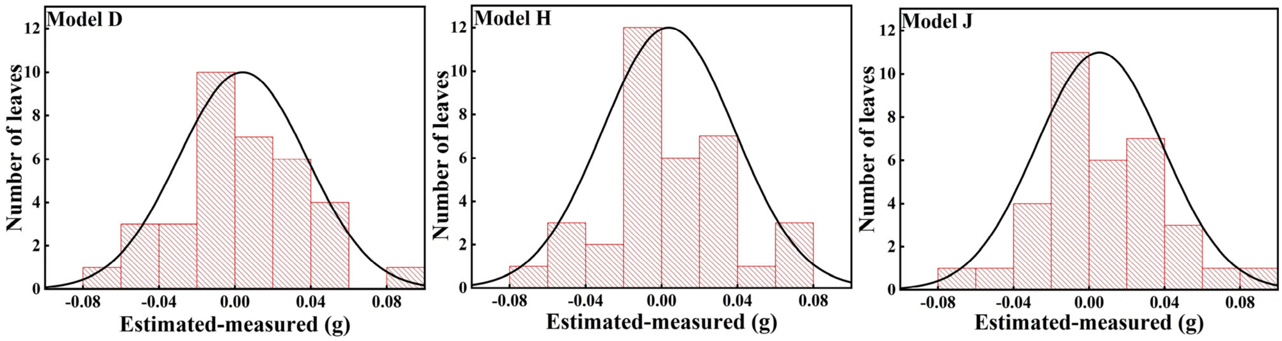

Figure 4. Error distribution in LDM estimations for *Bambusa multiplex* '*Willowy*'.

Both L·W and L·W·T can be used as variables for the LDM estimations of several leaf species, where T is the thickness of a leaf [11,12,22]. However, L·W rather than L·W·T was used for LDM estimations in this study because (1) the measurement of the thickness of a leaf is largely determined by the randomly selected positions of the uneven thickness leaf by operators; (2) the accuracy of the measurement tools produces uncertainties for soft and thin leaves; (3) good empirical relationships based on the power model between L·W and LDM have been proven for several leaf species, such as the leaves of *Ficus benjamina* (cv. Starlight) and *Tectona grandis* [11,22]; (4) leaf thickness is not correlated with SLA, and this has been confirmed by taxonomic relatedness tests on the basis of several plant species, including deciduous species, evergreens, shrubs, subshrubs, climbers and scramblers [32,33].

The hypothesis of diminishing returns represents the power relationship between LA and LDM using LA = $\beta \cdot \text{LDM}^{\gamma}$, where β and γ are unknown parameters of the model [34–36]. The value of γ is generally smaller than 1 to indicate that the increase in LDM is faster than that of LA because a leaf needs a larger dry mass to mechanically sustain larger leaf areas against drag forces and self-loading [37]. In this study, the γ values of the leaves of the 50 bamboo species were 0.83 $\pm$ 0.074, which is close to the γ value (0.87 $\pm$ 0.05) of five bamboo species estimated by Sun et al. [37]. Therefore, considering the power relationship between LDM and LA (R^2 = 0.89 and RMSE = 3.84 calculated based on the 50 bamboo species) and the good linear relationship between L·W and LA (Figure 2), the strong power relationship between L·W and LDM (Model H) was preferred for the 50 bamboo species.

Previous studies successfully estimated LDM, whether or not considering its vertical distribution of several types of leaves [11–13,22]. The maximal *MAE*% of the LDM of the 50 bamboo species was 12.5% $\pm$ 4.0% without considering the vertical distribution of LDM (Figure A3). Results had a smaller *MAE*% of LDM, compared with that in previous studies considering the vertical distribution of leaf weight, such as the five types of broad leaves (*MAE*% = 13.8% $\pm$ 3.6%) studied by Liu et al. [12], and the six types of broad leaves (*MAE*% = 17% $\pm$ 3.7%) explored by Gi et al. [13]. Therefore, the effects of the vertical distribution of LDM on the developed empirical relationships for the 50 bamboo species could be ignored in this study.

3.4. Models for SLA Estimations

The performance of all nine models was extremely good in $\overline{\text{SLA}}$ estimations (R^2 > 0.99 and RMSE < 1.88) (Figure 5). The minor discrepancy between measured and estimated $\overline{\text{SLA}}$s was from the models selected for LA and LDM estimations, respectively, especially the LDM models (Figure A3).

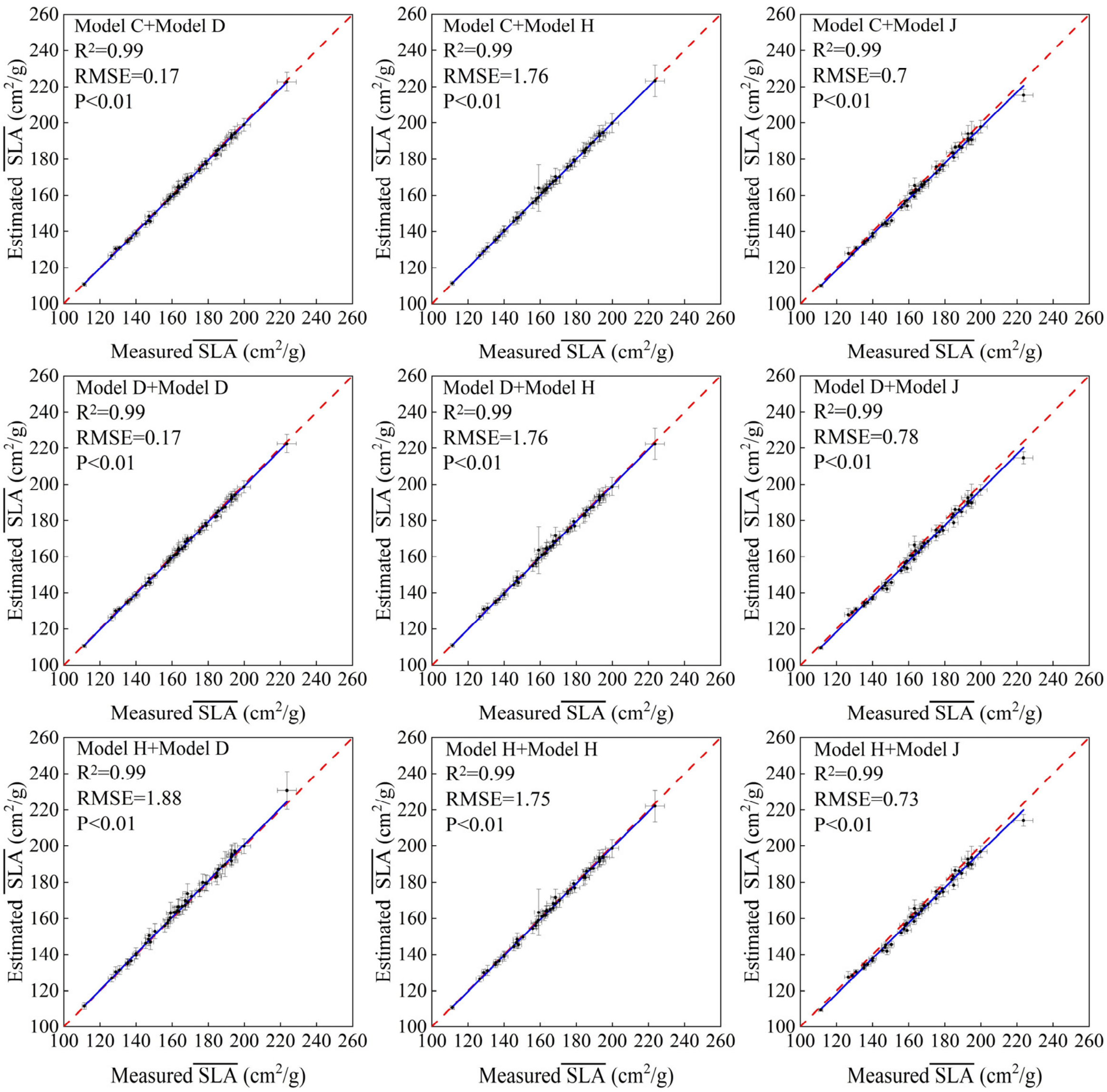

Figure 5. Validation of estimated $\overline{\text{SLA}}$s of the 50 bamboo species. Black spots represent the mean value of $\overline{\text{SLA}}$, and error bars are the standard deviation of $\overline{\text{SLA}}$ based on 40 model repetitions.

Although the $\overline{\text{SLA}}$s of the 50 bamboo species were successfully estimated on the basis of nine model combinations, this does not mean the empirical models were suitable for the SLA estimations of single leaves within a crown. Taking *Phyllostachys parvifolia* as an example (Table 1), the difference of the measured and estimated $\overline{\text{SLA}}$s was 3.28 cm^2/g, but the discrepancy between estimated and measured SLAs of single leaves ranged from −50.48 to 41.41 cm^2/g (Figure 6), indicating the significant variation in the SLAs of leaves within a crown. Therefore, the empirical models can be used for $\overline{\text{SLA}}$ estimations at the canopy scale but are not suitable for SLA estimations at the leaf scale because the deviation in LDM estimations was canceled out in $\overline{\text{SLA}}$ estimations.

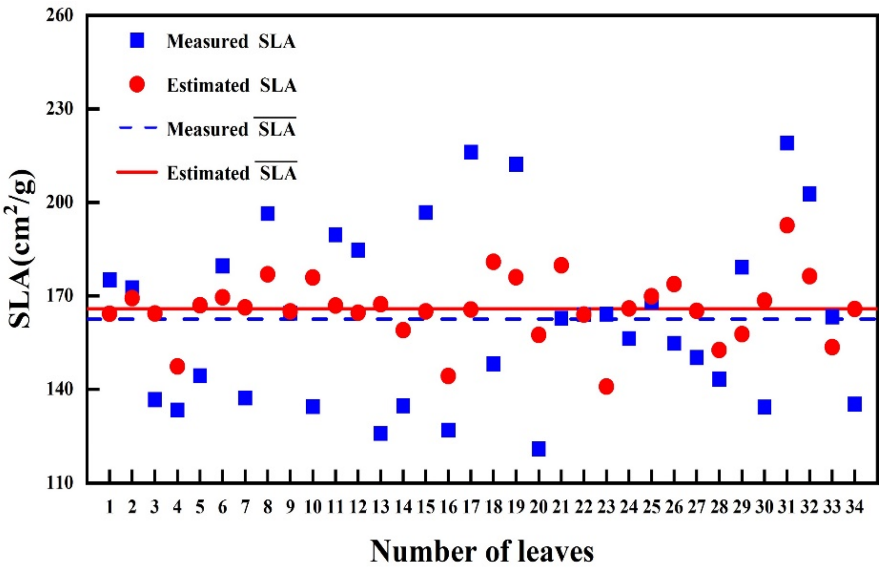

Figure 6. Measured and estimated SLAs of bamboo species *Phyllostachys parvifolia*. A total of 34 leaves represented 25% of the validation dataset of *Phyllostachys parvifolia* without multiple sampling.

4. Conclusions

This study provides cost-effective and recyclable nondestructive methods in estimating the SLA of 50 bamboo species at the canopy scale. On the basis of the strong correlations between leaf structural parameters and their $\overline{\text{SLA}}$, the L and W of leaves can further serve as powerful ways to nondestructively estimate the $\overline{\text{SLA}}$ of bamboo species and could be used as important indices for the ecological strategy of bamboo species. However, the empirical models developed for $\overline{\text{SLA}}$ estimations are not suitable for SLA estimations at the leaf scale because of the complex physiology and environmental conditions of a leaf. Although the L and W of leaves could be a good indicator for any field practitioner, the performance of the advanced models in this study should be further validated in future studies for more bamboo and other species. On the other hand, the leaf thickness is also worth to be considered to improve the LDM and SLA estimations of a single leaf based on nondestructive methods.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article. Raw data supporting the findings of this study are available from the corresponding authors on request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

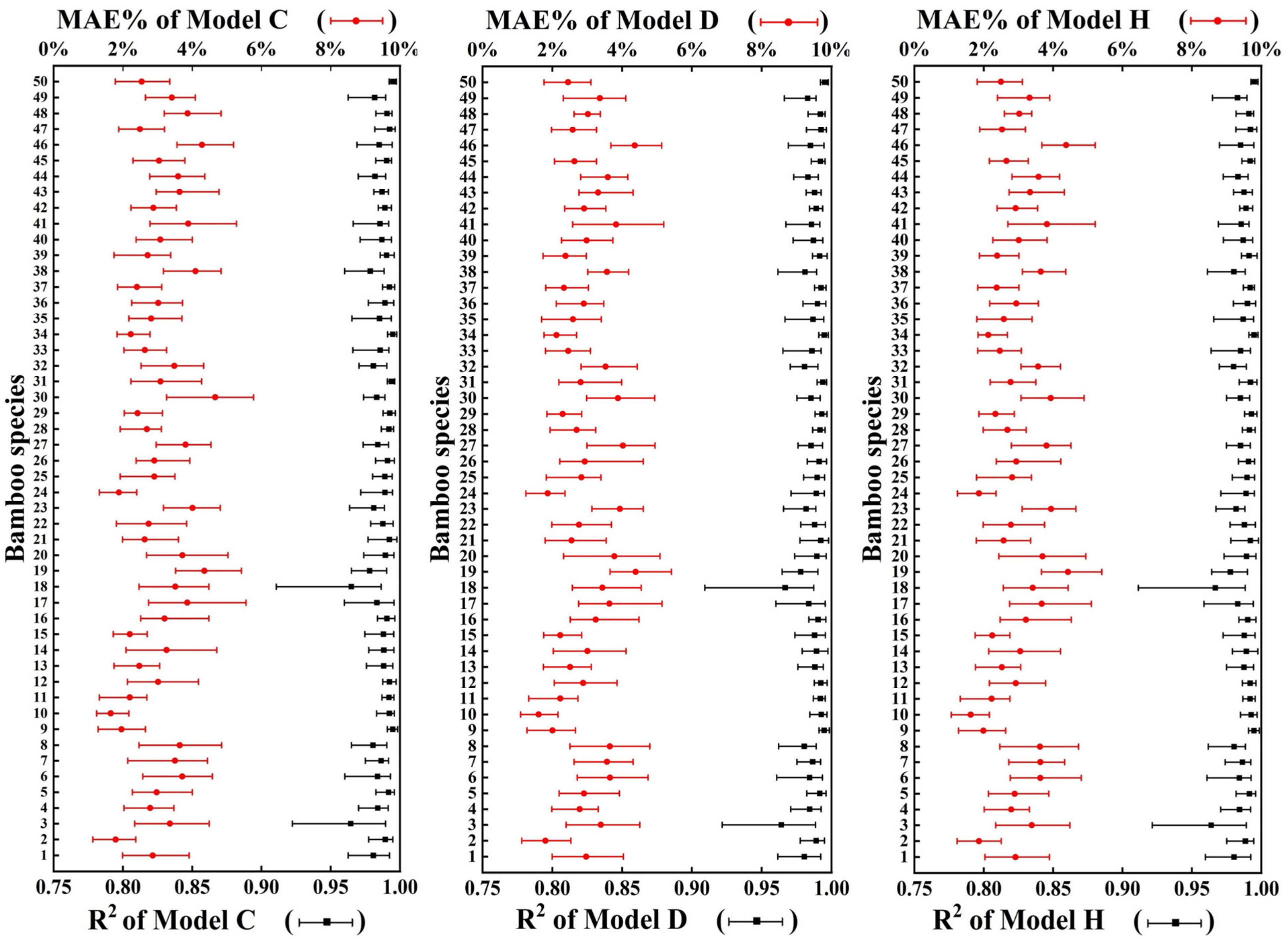

Figure A1. Validation of three selected models for LA estimations at leaf scale. Black spots and error bars represent the mean value and range of R^2 based on 40 model repetitions. Red spots and error bars represent the mean value and range of *MAE*% based on 40 model repetitions.

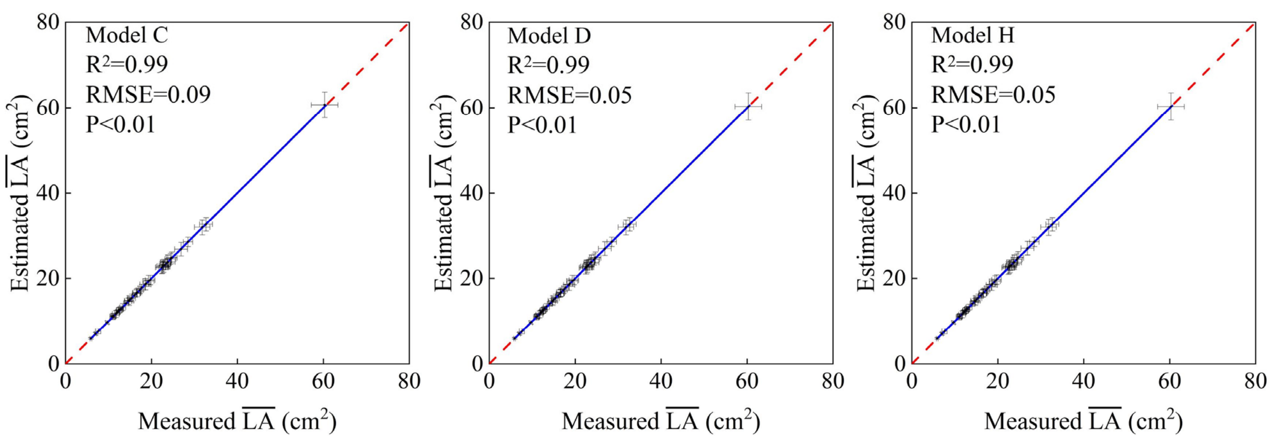

Figure A2. Validation of estimated $\overline{\text{LA}}$s of the 50 bamboo species at the canopy scale. Black spots represent $\overline{\text{LA}}$ s of the 50 bamboo species, and error bars are the standard deviation of $\overline{\text{LA}}$ based on 40 model repetitions.

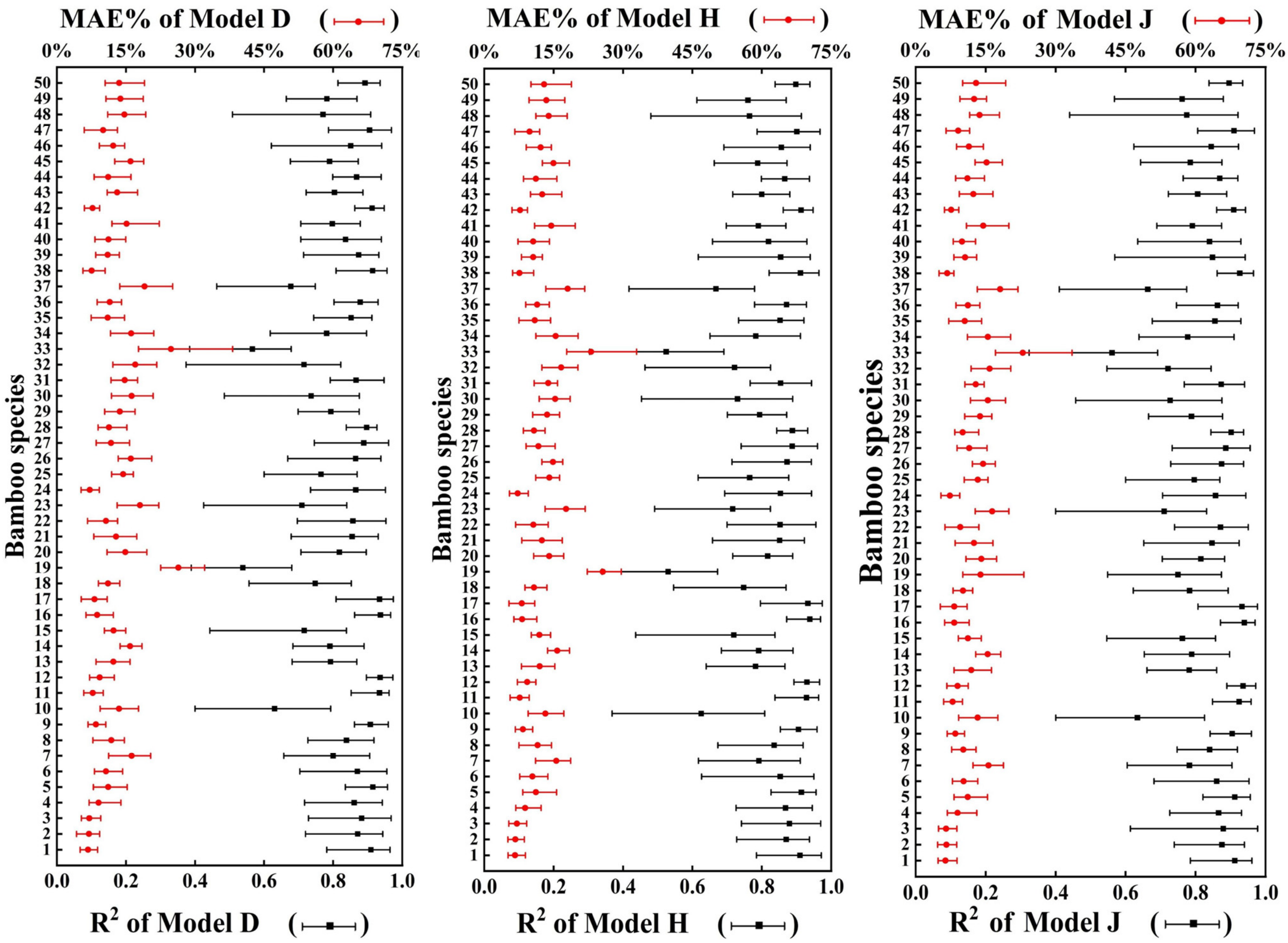

Figure A3. Validation of three selected models for LDM estimations at leaf scale. Black spots and error bars represent the mean value and range of R^2 based on 40 model repetitions. Red spots and error bars represent the mean value and range of *MAE*% based on 40 model repetitions.

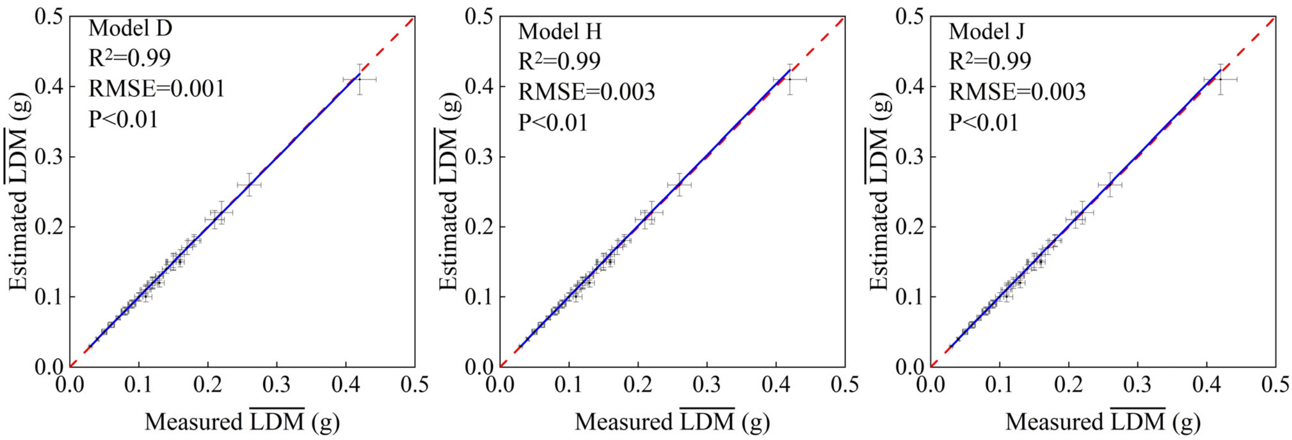

Figure A4. Validation of estimated $\overline{\text{LDM}}$s of the 50 bamboo species at the canopy scale. Black spots represent $\overline{\text{LDM}}$s of the 50 bamboo species, and error bars are the standard deviation of $\overline{\text{LDM}}$ based on 40 model repetitions.

Table A1. The mean values of the measured leaf parameters, leaf area and leaf dry mass of the 50 bamboo species. $\overline{\mathrm{L}}$, $\overline{\mathrm{W}}$, $\overline{\mathrm{LA}}$, and $\overline{\mathrm{LDM}}$ are the mean values of leaf length, leaf width, leaf area, and leaf dry mass, respectively. Δ is the standard deviation.

No.	Bamboo Species	$\overline{\mathrm{L}} \pm \Delta$ (cm)	$\overline{\mathrm{W}} \pm \Delta$ (cm)	$\overline{\mathrm{LA}} \pm \Delta$ (cm^2)	$\overline{\mathrm{LDM}} \pm \Delta$ (g)
1	*Shibataea chinensis* Nakai	8.0 ± 1.2	2.4 ± 0.3	12.7 ± 3.5	0.08 ± 0.02
2	*Shibataea nanpingensis* Q. F. Zheng & K. F. Huang	6.4 ± 0.8	2.2 ± 0.2	9.6 ± 2.2	0.05 ± 0.01
3	*Pseudosasa cantorii* (Munro) Keng f. in Y.L.Keng	14.3 ± 1.5	2.4 ± 0.4	23.6 ± 5.6	0.18 ± 0.05
4	*Phyllostachys nidularia* f. *vexillaris* Wen	10.0 ± 1.7	1.5 ± 0.2	11.1 ± 3.5	0.06 ± 0.03
5	*Oligostachyum spongiosum* (C. D. Chu & C. S. Chao) G. H. Ye & Y. P. Wang	14.2 ± 3.1	2.2 ± 0.4	22.7 ± 8.9	0.15 ± 0.07
6	*Phyllostachys longiciliata* G. H. Lai	10.8 ± 2.0	1.6 ± 0.3	13.5 ± 4.6	0.08 ± 0.04
7	*Pleioblastus amarus* var. *hangzhouensis* S. L. Chen & S. Y. Chen	13.0 ± 2.7	1.9 ± 0.4	18.6 ± 7.0	0.11 ± 0.04
8	*Phyllostachys rubicunda* T. W. Wen	10.5 ± 1.9	1.5 ± 0.2	12.2 ± 3.6	0.06 ± 0.02
9	*Phyllostachys nidularia* Munro	11.9 ± 2.0	1.9 ± 0.3	16.8 ± 5.3	0.11 ± 0.04
10	*Indosasa levigata* Z. P. Wang et G. H. Ye	14.2 ± 2.1	2.9 ± 0.3	28.7 ± 7.1	0.16 ± 0.05
11	*Phyllostachys platyglossa* Z. P. Wang & Z. H. Yu	11.4 ± 1.8	1.9 ± 0.3	15.4 ± 4.6	0.09 ± 0.03
12	*Pseudosasa japonica* 'Tsutsumiana'	17.0 ± 3.9	1.9 ± 0.4	23.8 ± 10.1	0.22 ± 0.10
13	*Phyllostachys aurita* J. L. Lu	11.8 ± 2.0	1.9 ± 0.3	16.5 ± 4.8	0.09 ± 0.03
14	*Phyllostachys meyeri* McClure	10.7 ± 2.2	1.5 ± 0.3	11.6 ± 4.2	0.06 ± 0.03
15	*Phyllostachys hispida* S. C. Li	10.8 ± 1.6	1.5 ± 0.2	12.1 ± 3.1	0.07 ± 0.02
16	*Pseudosasa japonica* f. *akebonosuji*	19.7 ± 3.2	2.2 ± 0.6	31.8 ± 12.3	0.26 ± 0.12
17	*Oligostachyum lubricum* (Wen) Keng f.	14.5 ± 3.3	1.9 ± 0.4	19.6 ± 8.4	0.12 ± 0.05
18	*Acidosasa chinensis* C. D. Chu et C. S. Chao	10.9 ± 1.4	2.0 ± 0.3	15.1 ± 3.7	0.09 ± 0.03
19	*Phyllostachys tianmuensis* Z. P. Wang & N. X. Ma	13.6 ± 2.4	1.7 ± 0.3	17.2 ± 5.6	0.11 ± 0.04
20	*Phyllostachys atrovaginata* C. S. Chao & H. Y. Chou	12.1 ± 2.9	1.9 ± 0.4	17.0 ± 7.0	0.11 ± 0.05
21	*Bambusa multiplex* 'Alphonso-Karrii' R. A. Young	12.4 ± 2.7	1.5 ± 0.3	14.7 ± 6.0	0.08 ± 0.03
22	*Phyllostachys robustiramea* S. Y. Chen & C. Y. Yao	11.7 ± 2.1	1.6 ± 0.3	14.1 ± 4.3	0.07 ± 0.03
23	*Sinobambusa yixingensis* C. S. Chao & K. S. Xiao	10.2 ± 1.8	1.7 ± 0.4	12.9 ± 4.4	0.08 ± 0.03
24	*Phyllostachys zhejiangensis* G. H. Lai	13.0 ± 1.8	2.1 ± 0.3	19.0 ± 4.7	0.14 ± 0.04
25	*Phyllostachys platyglossa* Z. P. Wang et Z. H. Yu	12.3 ± 2.2	1.8 ± 0.3	16.6 ± 5.4	0.11 ± 0.04
26	*Phyllostachys parvifolia* C. D. Chu & H. Y. Chou	7.6 ± 1.5	1.3 ± 0.3	7.6 ± 3.2	0.05 ± 0.03
27	*Bambusa multiplex 'Willowy'* R. A. Young	20.8 ± 4.7	1.7 ± 0.5	26.7 ± 10.5	0.21 ± 0.09
28	*Pleioblastus maculatus* (McClure) C. D. Chu & C. S. Chao	14.0 ± 3.3	1.9 ± 0.3	19.6 ± 7.5	0.12 ± 0.05
29	*Chimonobambusa unifolia* (T. P. Yi) T. H. Wen in D. Ohrnberger	10.4 ± 2.1	1.6 ± 0.3	12.1 ± 4.2	0.08 ± 0.03
30	*Pseudosasa amabilis* (McClure) Keng f. in Y. L. Keng	27.6 ± 6.2	3.1 ± 0.5	59.8 ± 22.3	0.42 ± 0.16
31	*Indosasa gigantea* (T. H. Wen) T. H. Wen	15.6 ± 4.0	2.0 ± 0.4	22.7 ± 10.0	0.15 ± 0.07
32	*Phyllostachys edulis* 'Heterocycla'	8.7 ± 1.6	1.1 ± 0.2	7.0 ± 2.1	0.04 ± 0.02
33	*Phyllostachys edulis* 'Tao kiang'	8.3 ± 1.4	1.0 ± 0.1	5.9 ± 1.6	0.03 ± 0.01
34	*Sinobambusa tootsik f. luteoloalbostriata* (S. H. Chen & Z. Z. Wang) T. P. Yi	11.8 ± 2.7	1.4 ± 0.3	12.6 ± 5.0	0.06 ± 0.03
35	*Phyllostachys aureosulcata* McClure	9.7 ± 1.9	1.5 ± 0.2	10.9 ± 3.5	0.08 ± 0.03
36	*Phyllostachys aureosulcata* 'Aureocaulis' Z. P. Wang et N. X. Ma	9.9 ± 2.0	1.5 ± 0.2	11.3 ± 4.0	0.08 ± 0.03
37	*Phyllostachys vivax* 'Aureocaulis' N. X. Ma	16.7 ± 2.9	1.9 ± 0.4	24.6 ± 8.2	0.17 ± 0.06
38	*Acidosasa edulis* (T. H. Wen) T. H. Wen	15.5 ± 2.8	2.0 ± 0.3	22.8 ± 6.8	0.13 ± 0.04
39	*Phyllostachys aureosulcata* f. *flavostriata*	10.5 ± 2.1	1.6 ± 0.2	12.5 ± 4.1	0.09 ± 0.03
40	*Phyllostachys aureosulcata* 'Spectabilis'	9.9 ± 2.0	1.5 ± 0.2	11.2 ± 3.8	0.08 ± 0.03
41	*Pleioblastus amarus* (Keng) Keng f.	15.0 ± 3.7	2.2 ± 0.3	24.3 ± 9.1	0.15 ± 0.06
42	*Pleioblastus ovatoauritas* Wen	17.8 ± 3.2	2.6 ± 0.4	33.1 ± 11.0	0.18 ± 0.06
43	*Sinobambusa intermedia* McClure	15.2 ± 3.2	2.1 ± 0.3	23.2 ± 8.2	0.13 ± 0.05
44	*Phyllostachys sulphurea* 'Houzeau' McClure	11.6 ± 2.2	2.0 ± 0.3	16.0 ± 5.2	0.12 ± 0.04
45	*Phyllostachys vivax f. viridivittata*	13.6 ± 2.6	1.8 ± 0.3	17.6 ± 5.7	0.10 ± 0.04
46	*Sinobambusa tootsik* var. *laeta* (Mcclure) Wen	15.7 ± 3.2	2.0 ± 0.5	23.2 ± 9.6	0.13 ± 0.06
47	*Pleioblastus gozadakensis* Nakai	14.9 ± 3.0	2.1 ± 0.4	23.7 ± 8.6	0.15 ± 0.06
48	*Sinobambusa tootsik* (Makino) Makino ex Nakai	14.8 ± 3.6	2.1 ± 0.4	22.1 ± 8.9	0.12 ± 0.05
49	*Pleioblastus chino* var. *hisauchii* Makino	20.1 ± 3.4	1.5 ± 0.4	22.5 ± 6.6	0.16 ± 0.05
50	*Bambusa multiplex* (Lour.) Raeusch. ex Schult.	12.5 ± 2.9	1.4 ± 0.3	14.6 ± 6.0	0.08 ± 0.04

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