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Allometric Models to Predict Total Height and Diameter at Breast Height (DBH) for the Flooded Forest Ecosystems in Cambodia

Model Alometrik untuk Memprediksi Tinggi Total dan Diameter Setinggi Dada (DBH) untuk Ekosistem Hutan Tergenang di Kamboja

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ABSTRACT

Reliable allometric equations are essential for estimating forest structure, biomass, and carbon stocks, which are still scarce in Cambodia's flooded forests. Therefore, this study aimed to develop predictive models for two key allometric relationships: (1) total tree height as a function of diameter at breast height (DBH) and (2) estimation of DBH from stump diameter when DBH measurements were unavailable. The analysis compared their performance using the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Akaike Information Criterion (AIC). The results showed that the logarithmic model performed optimally for Height–DBH relationship (R^2 = 0.494; RMSE = 2.59 m; AIC = 1738.9). The selected equation, $H = -1.7261 + 4.1124 \times \ln(DBH)$. DBH correlated strongly with stump diameter (r = 0.98, p < 0.001), with the power equation $DBH = 0.969 \times \text{Stump Diameter}^{0.983}$ as the best predictor. These stump-based relationships served as important tools in estimating biomass and carbon stocks in disturbed or logged forests where DBH could not be measured directly. Furthermore, the results showed the structural variability of Cambodia's flooded forests and provided practical allometric tools for forest inventory, biomass estimation, and carbon accounting under REDD+ initiatives.

INTISARI

Persamaan alometrik yang andal sangat penting untuk memperkirakan struktur hutan, biomassa, dan stok karbon, namun model tersebut masih langka untuk ekosistem hutan tergenang di Kamboja. Studi ini mengembangkan model prediktif untuk dua hubungan alometrik utama: (1) hubungan tinggi pohon dengan diameter setinggi dada (DBH) dan (2) estimasi DBH dari diameter tunggul ketika pengukuran DBH tidak tersedia dianalisis dan dibandingkan menggunakan koefisien determinasi (R^2), Root Mean Square Error *(RMSE), dan* Akaike Information Criterion *(AIC). Model logaritmik menunjukkan kinerja terbaik untuk hubungan tinggi–DBH (R^2 = 0,494; RMSE = 2,59 m; AIC = 1738,9). Persamaan terpilih, $H = -1{,}7261 + 4{,}1124 \times \ln(DBH)$. DBH berkorelasi kuat dengan diameter tunggul (r = 0,98; p < 0,001), dengan persamaan pangkat $DBH = 0{,}969 \times \text{Diameter Tunggul}^{0{,}983}$ sebagai prediktor terbaik. Hubungan berbasis diameter tunggul ini sangat penting untuk mendukung estimasi biomassa dan stok karbon pada hutan yang terganggu atau ditebang, di mana pengukuran DBH tidak dapat dilakukan secara langsung. Temuan ini menyoroti variabilitas struktural hutan tergenang di Kamboja dan menyediakan alat alometrik praktis untuk inventarisasi hutan, estimasi biomassa, dan perhitungan karbon dalam inisiatif REDD+.*

Introduction

Accurate allometric equations are essential for estimating tree height and diameter-based parameters such as aboveground biomass (AGB), which are fundamental for forest carbon measurements and ecological studies (Chave et al. 2014). Tree allometry uses easily measurable traits such as diameter at breast height (DBH) to estimate more resource-intensive variables like height and biomass. Globally, height–diameter allometric relationships have been widely developed across diverse forest ecosystems, including tropical rainforests, temperate forests, riparian systems, and mangrove forests (Yang & Swenson 2023). Several studies have shown that incorporating tree height into allometric models improves biomass estimation accuracy and reduces uncertainty in carbon stock assessments (Yang & Swenson 2023; Terryn et al. 2024). Previous reports have also observed significant variability in height–diameter relationships driven by species composition, stand structure, site conditions, and hydrological regimes (Zhang et al. 2020; Gallerani et al. 2025). This shows that the direct transfer of allometric equations across regions or forest types often leads to biased estimates, suggesting the need for locally calibrated models. However, the relationship between height and diameter (height–DBH) varies significantly across forest types and biogeographic regions, making general models for the tropics biased and inaccurate (Gallerani et al. 2025).

The variability across regions shows the need for developing site-specific allometric models, particularly for complex ecosystems such as flooded forests, where hydraulic factors and unique growth characteristics affect tree structure (Ogwu et al. 2025). Additionally, national carbon monitoring programs, such as Cambodia's REDD+ report, use height–diameter equations that are adjusted for each forest type (Kim et al. 2023). Despite these efforts, robust allometric studies for flooded forests in Cambodia are still limited. These areas often experience seasonal flooding with a unique tree species composition producing different height–diameter relationships than valley and permanent forests. In addition to standing-tree measurements, forest inventories in disturbed, degraded, or logged forests frequently encounter situations where DBH cannot be measured directly because trees have fallen or been harvested (DellaSala et al. 2022). Under these conditions, stump diameter is the only remaining measurable attribute and can be used to reconstruct DBH as well as estimate residual biomass and carbon stocks (Mugasha et al. 2021). Therefore, stump-based allometric relationships are essential for post-harvest assessment, forest degradation monitoring, and long-term carbon accounting, which have not been widely reported for flooded forests in Cambodia (Sasaki & Vijitharan 2024). In disturbed or logged forests, stump diameter can be used as a proxy for DBH when full-grown trees are no longer present to estimate dead or residual stump mass.

Based on the description above, this study aims to develop and evaluate regionally adjusted models for two key allometric relationships in Cambodia's flooded forests, by predicting tree height from DBH and estimation of DBH from stump diameter. By comparing various equations, including linear, logarithmic, power, exponential, and asymptotic equations, this study aims to identify the most accurate and appropriate equations for the height–diameter and stem–diameter relationships. The developed models will help to improve the accuracy of assessing biomass and carbon stocks in Cambodia's unique flooded forest landscapes.

Methods

Study Area

This study examined Cambodia's flooded forest ecosystems surrounding the Tonlé Sap Great Lake, particularly across the provinces of Kampong Chhnang, Pursat, Kampong Thom, Siem Reap, and Battambang. Seasonal flooding characterizes these ecosystems, supports a wide variety of tree species capable of surviving prolonged inundation, and plays a crucial role in biodiversity conservation and carbon storage. Although several studies conducted between 2015 and 2023 have reported the ecological importance of Tonlé Sap's flooded forests, there is limited infor-mation on the structural allometry and biomass modeling in these ecosystems. The Tonlé Sap flooded forest is located in central Cambodia within the Lower Mekong Basin and represents one of the largest seasonally inundated forests in Southeast Asia

(Figure 1). Based on observation, flooding duration and depth vary spatially and temporally, creating strong environ-mental gradients that influence tree growth form and stand structure. To capture the spatial variability, this study established 30 sampling plots across the four provinces. The selected plot represented typical flooded forest conditions, as shown in Figure 1.

Data Collection

This study collected field data from 30 randomly established forest plots and measured all trees with DBH of ≥ 5 cm. Measurement of tree attributes followed specific procedures, included DBH (cm) measured with a diameter tape 1.3 m above the ground, total height (m) measured using a laser rangefinder or hypsometer, bole height (m) as the distance to the first major branch or crown base, and stump diameter at the cut surface, typically 20–30 cm above the ground, for trees that were cut or left standing. Logged or naturally fallen trees provided both DBH and stump diameter from the same individual trees. In the case of recently felled trees, DBH measurement occurred at 1.3 m above the original ground level before or immediately after felling, and stump diameter at the cut surface. For fallen trees with intact stems, DBH measurement occurred along the stem axis using standard forestry protocols. This method generated paired DBH–stump diameter data suitable for regression modeling.

Model Development

Field measurement captured DBH and total height for 913 trees as well as bole height and stump diameter for 368 and 234 trees, respectively. The number of trees differed among variables because not all measurements could be collected during every field campaign. In some years, seasonal flooding, dense understory, and limited visibility restricted access to the lower stem, preventing consistent bole height measurements. Furthermore, logged or naturally fallen trees during surveys produced stump diameter data, resulting in a smaller sample size. In comparison, DBH and total height received priority across all years because the two variables formed the most essential for allometric model development. This study developed two groups of predictive models. The first group examined the height–DBH relationship

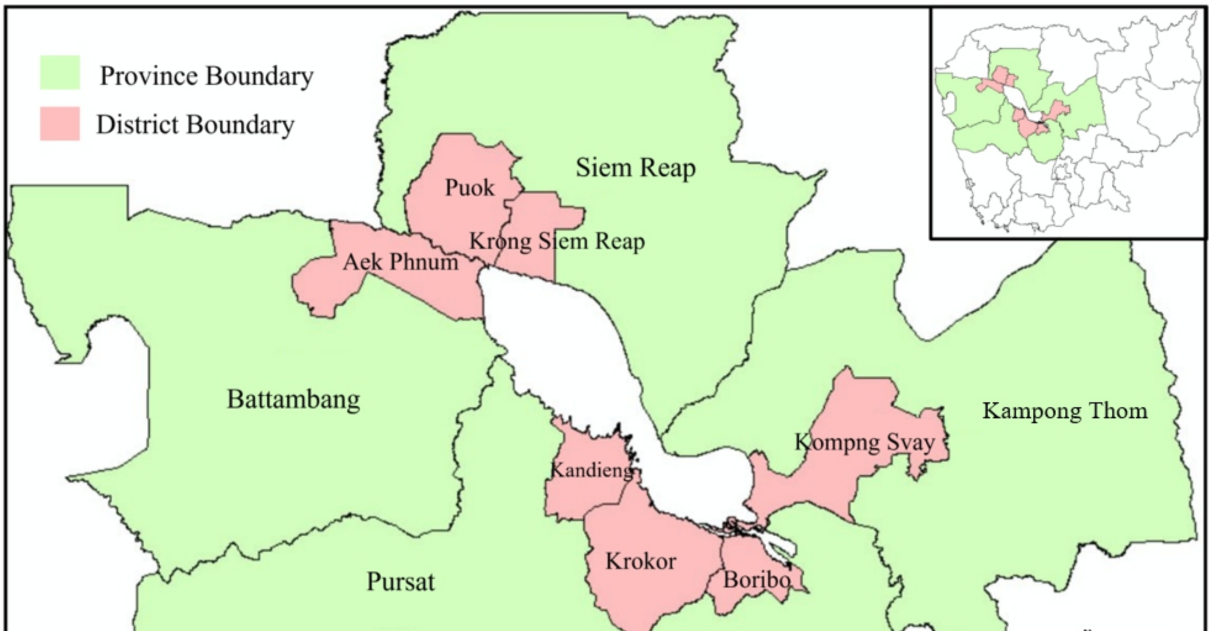

Figure 1. Map of study area

using seven regression equations, namely linear, logarithmic, power, exponential, polynomial, logistic, and asymptotic, to capture a range of biologically plausible growth patterns reported in previous allometric studies. The second group tested four functions, including linear, power, exponential, and logarithmic, for estimating DBH from stump diameter, showing the near-linear taper typically observed in tree stems. Furthermore, the analysis divided the dataset into 70% for model training and 30% for validation, ensuring robust fitting and a realistic assessment of predictive accuracy.

Model Fitting and Evaluation

This study performed model fitting in Python using the statsmodels and scipy.optimize.curve_fit libraries. The analysis evaluated model performance based on several criteria and determined goodness of fit by using the coefficient of determination (R^2). Error analysis quantified by the Root Mean Square Error (RMSE) measured prediction accuracy. This study selected the best model by comparing candidate models using the Akaike Information Criterion (AIC), where lower AIC values showed a better balance between goodness of fit and model simplicity. The statistical significance of regression coefficients (parameters a, b, and c) was tested using P-values (α=0.05). Subsequently, residual diagnostics measured model assumptions through visual inspection of residual normality and homoscedasticity. The independent validation dataset (30% of the data) assessed model validation, while predictive performance used Mean Error (ME), Percentage Error (PE), Root Mean Square Error of Prediction (RMSEP), and Mean Absolute Percentage Error (MAPE). The first model group examined the Height–DBH relationship using seven regression equations, while the second group tested four functions for estimating DBH from stump diameter. The analysis divided the dataset into two parts, namely 70% training and 30% validation. In all equations, parameters a, b, and c represent fitted regression coefficients describing intercept, scaling, and curvature terms, respectively.

Statistical Analysis and Visualization

This study evaluated model fit using scatterplots with regression curves and performed residual analysis to identify possible systematic bias. Correlo-grams, bubble plots, and three-dimensional surface plots showed the relationships among DBH, tree height, and stump diameter. All statistical analyses and visualizations used Python with standard scien-tific libraries, including Pandas, NumPy, Matplotlib, Seaborn, and SciPy. The analysis generated boxplots with overlaid jittered points to visualize combined relationships among DBH, stump diameter, and total height.

Result and Discussion

Descriptive Statistics of Tree Measurements

This study measured a total of 913 trees in Cambodia's flooded forests, including 368 bole heights and 234 stump diameters (Table 1). Differences in sample size among variables showed field constraints typical of flooded forest, where measurement of bole height and stump diameter was for accessible or logged trees, while priorities included DBH and total height across all plots. The mean diameter DBH at 37.9 ± 21.2 cm ranged from 3.9 to 149.2 cm, showing a right-skewed distribution (skew = 1.0; kurt = 1.1). This shows that most trees are small to medium-sized, with few large stumps. The pattern observed is common in natural tropical forests, where growth and mortality processes produce an uneven structure (Baia et al. 2025; Gora et al. 2025). The mean bole height at 5.5 ± 3.0 m, and the total height of 12.5 m (± 3.6) showed a slight rightward skew (skew = 1.0 and 0.3, respectively), indicating that most trees were in the low height class, while only a few were in the high height class. This difference shows the influence of waterlogging and light competition, which are

Table 1. Descriptive statistics of tree measurements used in model development.

Variable	Count	Mean	SD	Min	Max	Variance	Skew	Kurt
DBH (cm)	913	37.9	21.2	3.9	149.2	450.5	1	1.1
Bole Height (m)	368	5.5	3	3	15	8.7	1	0.8
Total Height (m)	913	12.5	3.6	3	23	13.2	0.3	−0.1
Stump Diameter (cm)	234	50.7	25	5.3	117	621.6	0.5	−0.4

common characteristics of flooded forest ecosystems (Zhang et al. 2020; Keller et al. 2024). The stump diameter has a mean value of 50.7 ± 25.0 cm and is slightly skewed (skew = 0.5), showing moderate size variation without any extreme values. The skewness (0.3–1.0) and kurtosis (−0.4 to 1.1) values are within the normal range for natural forests, which generally do not have high standard deviation due to different age factors and growth conditions. The results show that Cambodian flooded forests are predominantly composed of small to medium-sized trees, with few large trees contributing significantly to the variation in structure and mass. This variation in tree size shows natural and unnatural growth processes that are inherent to flooded ecosystems, providing a basis for developing allometric models for accurate mass and carbon estimation.

DBH Variation by Species

Forest plots of mean diameter at base (DBH ± SE) by tree species in the flooded forests showed clear species differences (Figure 2). The dotted red line showed the mean overall DBH of approximately 38 cm. Some tree species, such as *Terminalia cambodiana*, *Barringtonia micrantha*, *Barringtonia acutangula,* and *Diospyros cambodiana*, showed mean diameters close to or slightly above the mean overall, representing medium-sized trees, which were typical of older flooded forests. In comparison, *Crudia chrysantha* had the highest mean diameter and showed the greatest variability, showing that there were few large trees, contributing significantly to the basal area and mass of the forests. Tree species, such as *Hymenocardia wallichii, Garcinia cochinchinensis,* and *Dalbergia horrida,* showed the lowest mean DBH, indicating dominance of young trees or slow-growing species suitable for shaded or frequently flooded areas. These differences between species are consistent with previous observations, suggesting that flooded forests are highly spatially diverse, showing species tolerance to waterlogging, light availability, and soil oxygen levels (Savacinski et al. 2023). The different DBH patterns show the functional diversity from fast-growing, large tree species at the top of the canopy (such as *Crudia chrysantha*) to small or shade-tolerant species at the bottom. This structural diversity is a key factor in increasing the resilience and productivity of flooded forests. Therefore, species-specific allometric equations are recommended to improve the accuracy of estimating mass and carbon stocks in an environment prone to periodic changes in water. Although species-specific allometric equations may further improve accuracy, this study adopts mixed-species models to provide practical tools applicable across flooded forest stands, where species-level sample sizes are often insufficient for robust model development.

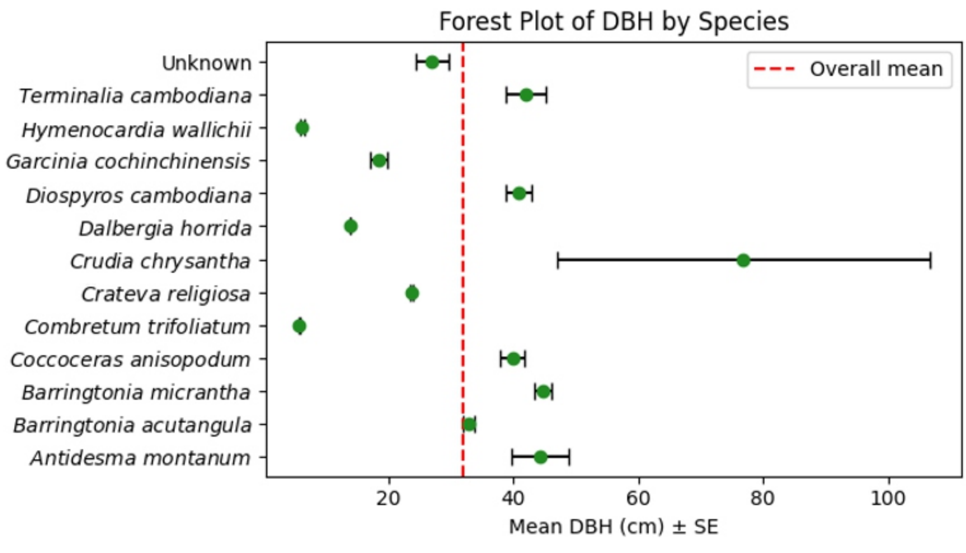

Figure 2. Mean diameter at breast height (DBH) ± standard error (SE) of dominant tree species in the study area. The red dashed line represents the overall mean DBH across all species. Error bars show the variability among sampled individuals within each species.

Variation of Tree Measurements

Figure 3 shows the differences between the four tree variables measured in the flooded forests of Cambodia. Based on the results, DBH and stump diameter showed the widest range and many outliers, indicating significant structural differences in the stump. The presence of many large-diameter trees showed an uneven age distribution and mixed growth stages, which were characteristic of natural or semi-natural flooded forests experiencing continuous regeneration and mortality cycles (Bren et al. 2025). In comparison, stump height showed the least variability, with a mean value of approximately 5–6 m, while peak height ranged from 3 m to 23 m and had a mean of 12–13 m. This limited height variability shows environmental constraints such as periodic flooding and low soil oxygen availability, which restrict vertical growth but allow for lateral expansion of stump diameter (Freschet et al. 2021). The observed patterns show that flooded forests in Cambodia are heterogeneous ecosystems, dominated by small to medium-sized trees, but with few large trees contributing disproportionately to total biomass and carbon stocks (Baia et al. 2025). These variations show the ecological complexity of flooded forests and emphasize the importance of incorporating differences in tree size into biomass and carbon modeling frameworks.

Species Composition

Treemap of tree species structure (Figure 4) showed that the flooded forest community is dominated by *Barringtonia acutangula* (n=276) and followed by *Barringtonia micrantha* (n=228), accounting for more than half of the total sampled trees. Other tree species with moderate abundance included *Coccoceras anisopodum* (n=184) and *Diospyros cambodiana* (n=88), while *Terminalia cambodiana* (n=59) and *Garcinia cochinchinensis* (n=32) were less abundant. Some minor tree species, such as *Hymenocardia wallichii*, *Antidesma montanum*, *Crudia chrysantha*, and *Combretum trifoliatum*, were found in fewer than 10 trees. This pattern of coverage suggests that flooded forest ecosystems are built on a small number of tree species that are highly tolerant of prolonged flooding and oxygen-deficient soils, particularly Barringtonia species, typical of riverine forests throughout Southeast Asia (Parolin & Wittmann 2010). The coexistence of a large number of small tree species suggests niche diversification and successional dynamics that help maintain overall biodiversity despite high environmental pressures. This pattern of uneven coverage is typical of tropical riverine forest systems, where flooding pressures and natural disturbances help select for highly tolerant tree species, with smaller species inhabiting sub-zones. Overall, Treemap shows tree species structure that is influenced by environmental filtering and ecological specialization. The high prevalence of Barringtonia is important in shaping forest structure, biomass, and carbon storage, while the inclusion of rare species helps add complexity and resilience to flooded forest ecosystems.

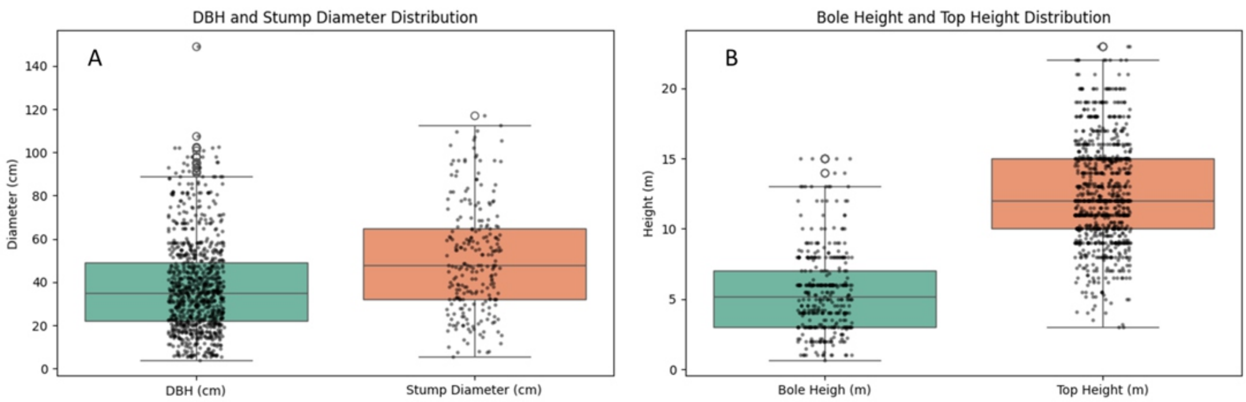

Figure 3. Boxplots with overlaid jittered points showing the distribution of tree structural measurements. (A) shows diameter at breast height (DBH) and stump diameter. (B) presents bole height and top height. Boxes show the interquartile range (IQR), central horizontal lines represent medians, whiskers extend to values within 1.5×IQR, and individual points show observed measurements; open circles denote outliers.

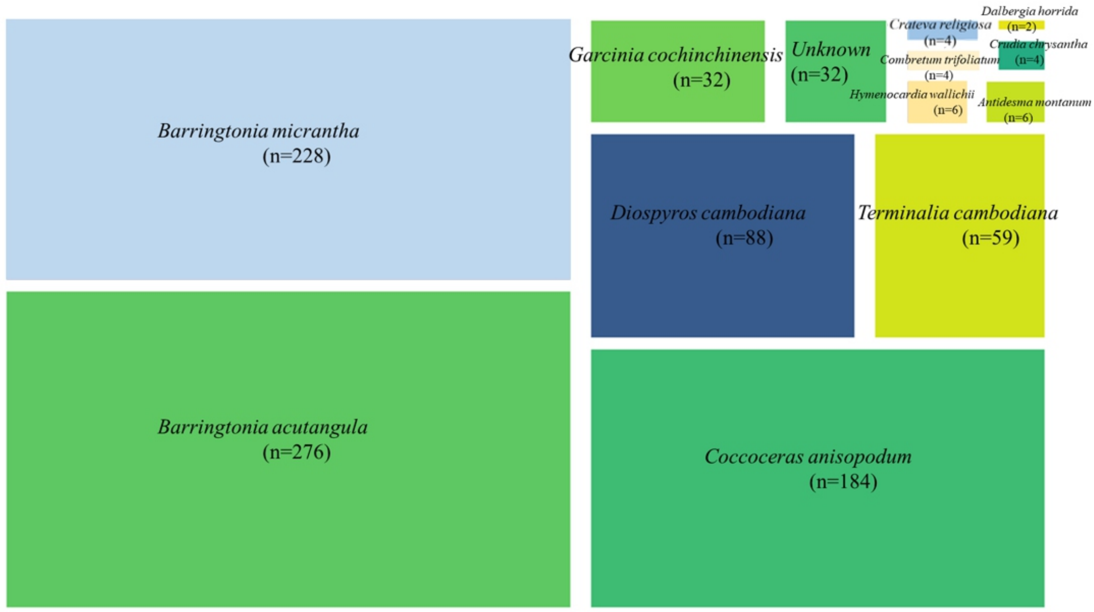

Figure 4. Treemap showing the relative abundance of dominant tree species in the study area based on sample size (n). The area of each rectangle represents the proportion of individuals for each species, showing *Barringtonia acutangula* and *Barringtonia micrantha* as the most abundant species, followed by *Coccoceras anisopodum* and *Diospyros cambodiana*.

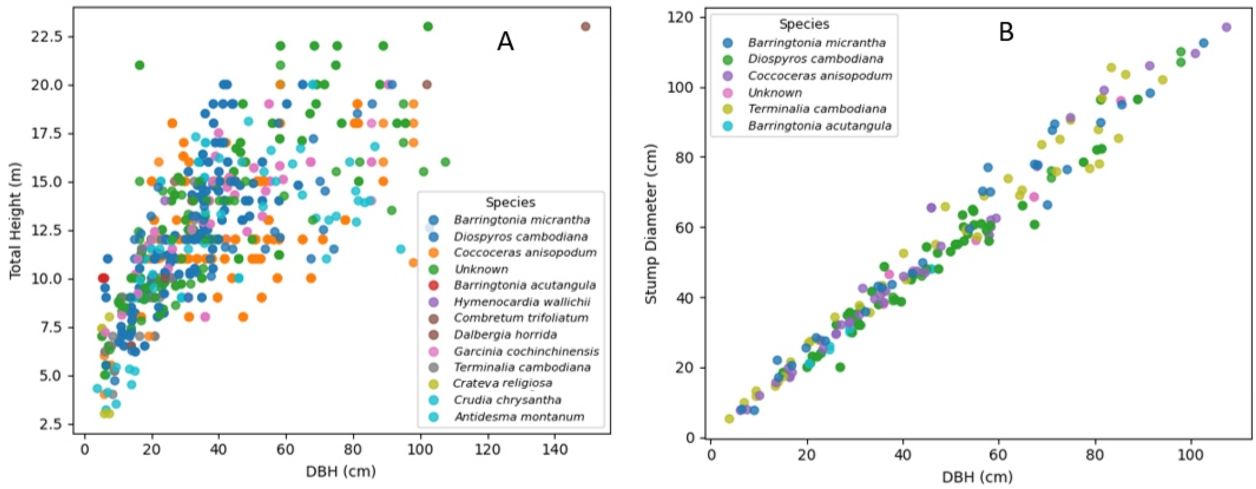

Figure 5. Relationships among key tree size variables by species. (A) Scatterplot of total height (m) versus DBH (cm). (B) Scatterplot of stump diameter (cm) versus DBH (cm). Points represent individual trees and are colored by species (see legend). Overall, total height increased with DBH with greater variability at larger diameters, while stump diameter showed a strong, near-linear increase with DBH across species.

Relationship of DBH and Stump Diameter

The three-dimensional surface plot showed the relationship between top height, DBH, and stump diameter, calculated using a linear regression model (Figure 5). Both DBH and stump diameter showed a positive relationship with top height, indicating that trees with larger diameters tended to grow towards greater heights. This pattern is consistent with allometric principles in tropical and riverine forests, where tree height tends to increase with diameter until maturity, when growth stops rapidly (Pumijumnong et al. 2023). Although the fitted plane model can capture the general upward trend properly, there are still many different interpretations of the regression surface, showing considerable variability between trees and tree species. The diversity suggests the influence of multiple biological and environmental factors, such as tree species growth strategies, flooding frequency, and

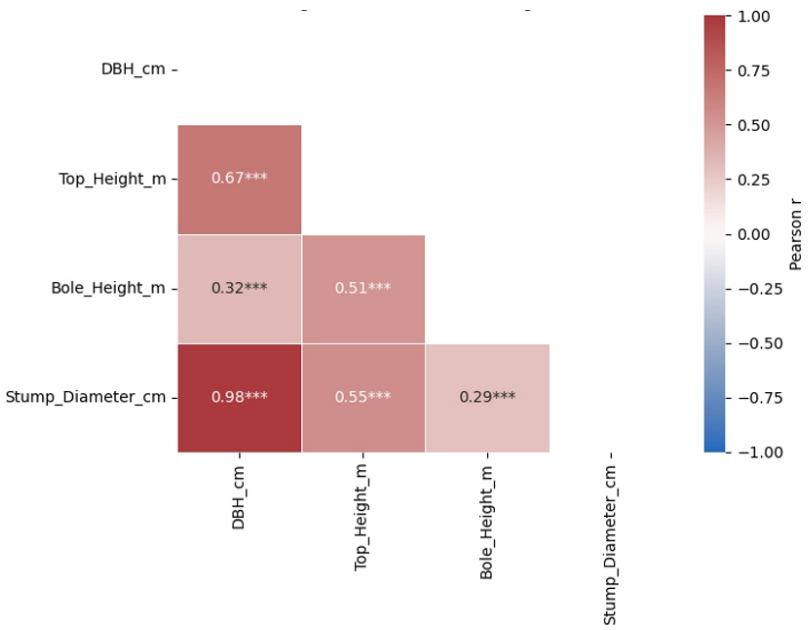

Figure 6. Correlogram showing Pearson correlation coefficients among tree measurement variables, including DBH, stump diameter, top height, and bole height. The intensity of color represents the strength and direction of the correlation, with darker red showing stronger positive relationships. Asterisks (***) denote statistically significant correlations at $p < 0.001$.

soil conditions, which can disrupt the direct relationship between diameter and height (Holeštová et al. 2024). The observed positive relationships suggest that DBH and stump diameter are valid predictors of tree height in flooded forests. However, the observed variability shows the need to develop tree species-specific or mixed-effect allometric models to control for ecological and structural differences when generating height–diameter equations for estimating mass.

Correlation among Tree Variables

The correlogram showed a statistically significant positive relationship between DBH, stump diameter, stem height, and crown height, indicating a systematic relationship between tree traits (Figure 6). DBH and stump diameter had a strong and approxi-mately perfect correlation ($r = 0.98$, $p < 0.001$), showing a close relationship between the two measurements representing the same dimension along the stump. Similarly, DBH also showed a strong positive relationship with crown height ($r = 0.67$, $p < 0.001$), indicating that trees with larger diameters tended to grow to greater heights, consistent with allometric growth patterns reported in tropical and subtropical forests (Terryn et al. 2024; Mangalam et al. 2024). Stem diameter showed a strong positive correlation with total height ($r = 0.55$, $p < 0.001$) and a moderate correlation with stem height ($r = 0.29$, $p < 0.001$), suggesting that basal diameter could be used as a predictor of vertical growth. Stem height showed a moderate correlation with both stem diameter ($r = 0.32$, $p < 0.001$) and total height ($r = 0.51$, $p < 0.001$), showing species-specific differences in crown formation and competition within the stem (Sharma et al. 2022). The strong correlation between stem diameter and height variables showed the reliability of using diameter-based indices for predicting tree height and mass in flooded forests. However, the moderate correlation with stem height suggests that species-specific shape and environmental constraints are also important factors in the variability of forest structure. All reported correlations showed statistical significance ($p < 0.001$), supporting the use of diameter-based predictors in another allometric modeling. Therefore, this study recommends using allometric equations by tree species or mixed effects models to improve the accuracy of mass predictions.

DBH, Stump Diameter, and Height Relationships

The bubble plot showed the relationship between DBH and top height, with bubble size representing stump diameter and species color-coded (Figure 7). Based on observation, the plot showed a strong positive trend, with trees with larger DBH achieving higher heights. This pattern is consistent with the correlation results in Figure 5, showing that stump diameter is a reliable predictor of height growth in submerged forest species (Mancheño et al. 2024). Larger bubbles cluster at higher DBH values, showing a near-linear relationship between DBH and stump diameter and supporting their close structural relationships. Further observations show a species-level pattern according to the plot pattern. *Barringtonia acutangula*, *Barringtonia micrantha*, and *Coccoceras anisopodum* occupied the widest range of DBH and height, showing the dominance and structural importance in the stump. In comparison, *Diospyros cambodiana* and *Hymenocardia wallichii* were clustered in smaller size classes, showing slower growth rates or adaptation to subsurface conditions. The spread of points at mean DBH values showed differences between specific height development traits, influenced by growth form, ecological niche, and flood tolerance (Rahman et al. 2021). The results suggest that while DBH and stump diameter are strong predictors of tree height, species-specific growth strategies and environmental interactions account for the observed variability. Therefore, incorporating species identity into allometric modeling will increase the precision of biomass and carbon stock estimates in Cambodian flooded forest ecosystems. The observed interspecific variation further explains the moderate prediction error of mixed-species models and supports future development of species-specific or multilevel allometric frameworks.

Development and Fitting of Allometric Equations between Height and DBH

This study evaluated seven regression models (M1–M7) to develop an allometric equation to describe the relationship between tree height and DBH in the flooded forests of Cambodia (Table 2). The experimental models included Linear (M1), Logarithmic (M2), Exponential (M3 and M4), Polynomial (M5), Logistic (M6), and Weibull/Asymptotic (M7), representing different biological growth parameters. Model comparisons based on the regression ratio (R^2), mean square error (RMSE), and Akaike's index (AIC) showed that the logarithmic model (M2: height = a + b ln(DBH)) performed best. This model has the highest R^2 value, and the lowest AIC and RMSE, showing high interpretability and predictive accuracy while maintaining the simplicity of the equation. The exponential model (M3) also performed well, capturing the nonlinear nature of the height– diameter relationship. However, other exponential models and Weibull-type

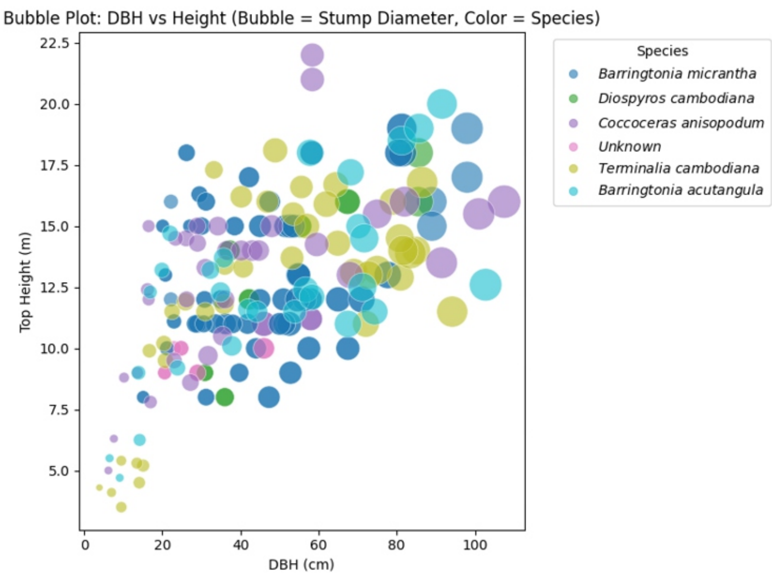

Figure 7. Bubble plot showing the relationship between DBH and top height across dominant tree species. Each bubble represents an individual tree, with bubble size corresponding to stump diameter and color showing species identity. The plot shows a positive association between DBH and top height, with interspecific variation in growth patterns.

Table 2. Type of model for allometric equation

Model	Model Form	Types of Regression
M1	Height = (a + b) x DBH	Linear Regression
M2	Height = (a + b) x ln (DBH)	Logarithmic Regression
M3	Height = a x (DBH^{b})	Power Regression
M4	Height = a x $e^{(b \times DBH)}$	Exponential Regression
M5	Height = (a + b) x DBH+ c x DBH^2	Polynomial Regression
M6	Height = a/1 + $e^{-(b \times (DBH-c))}$	Logistic Regression
M7	Height = a $(1-e^{-b \cdot DBH \wedge c})$	Weibull / Asymptotic

Source: Curtis & Marshall (2000), Pretzsch (2009), and Chave et al. (2014)

models were inadequate, overpredicting the true height for trees with large diameters.

The dominant result of the logarithmic model is that tree height in flooded forests increases rapidly at an early age (small diameter) but tends to stabilize at maturity. This is consistent with general biological theory and results from studies in tropical forests and riverine areas. Models that assume exponential growth or a decline in height at large diameters, as observed in some polynomial and exponential models, are considered biologically inappropriate, particularly when statistically appropriate. The results show that the height–diameter relationship in Cambodian flooded forests is best represented by a logarithmic model, which balances statistical reliability with ecological appropriateness. This equation accurately represents the rate of height growth that decreases with increasing diameter, showing resource constraints and natural mechanical factors of older trees (Zhang et al. 2020; Koreň et al. 2024). The selected model provides a reliable basis for height prediction and mass studies in flooded forest systems with complex structures.

Height–DBH Model Development and Fitting

This study evaluated seven functional forms to describe the relationship between tree height and DBH in the flooded forests of Cambodia (Figure 8a–g; Table 4). The tested models were linear, logarithmic, power, polynomial (quadratic), logistic, Weibull, and exponential equations. The comparison of model performance used the coefficient of determination (R^2), RMSE, and AIC.

Among the tested models, the logarithmic equation:

H = - 1.7261 + 4.1124 x ln(DBH) .... *Equation 1*

The results showed that all regression coefficients were statistically significant ($p < 0.05$), and residual diagnostics confirmed approximate normality and homoscedasticity. Independent validation using 30% of the dataset produced consistent RMSE and low prediction bias, supporting model robustness. The logarithmic model (Equation 1) provided the best overall fit (R^2 = 0.494, RMSE = 2.586 m, AIC = 1738.9), explaining approximately half of the variation in tree height while maintaining low prediction error and model simplicity. The power model was a close competitor (R^2 = 0.492, ΔAIC = 3.5), showing a similarly strong but slightly less efficient fit. The logistic model also performed moderately well, producing a biologically meaningful asymptote (~16.6 m), but with weaker statistical support (AIC = 1759.2). In comparison, the polynomial and linear models showed low explanatory power and produced unrealistic height predictions at extreme DBH values. The Weibull and exponential models failed to represent the observed pattern, leading to poor fits and implausible outputs (AIC > 2300).

Visual inspection of the fitted curves confirmed that the logarithmic and power functions captured the observed height–diameter relationship most accurately, particularly at small DBH classes, where height increased rapidly before reaching a steady state in large trees (Figure 8a–g, Table 3). This model showed the typical allometric behavior in tropical and old-growth flooded forests, where height growth rates decreased as mechanical constraints and resource competition increased (Norghauer 2021). The best performance of the logarithmic model was consistent with results from other tropical forest studies (Rex et al. 2020), reporting that height gain decreased with increasing DBH due to environmental stressors such as flooding and soil oxygen depletion (Wan et al. 2024). In line with the analysis, the logarithmic model provides both statistical robustness and ecological suitability, making it the most suitable function for predicting tree height from DBH in flooded forests in Cambodia. The simplicity and accuracy of this model support the application in estimating biomass and carbon stocks, where accurate height prediction is important but direct measurements are often hindered by large tree sizes and flooded soils. Therefore, the developed model provides a practical

Table 3. Allometric equation model.development.

Model	R^2	RMSE	Parameters (coefficients)	k	AIC	p-value	Rank
Logarithmic	0.494	2.586	a = -1.7261, b = 4.1124	2	1738.9	0.001	1
Power	0.492	2.591	a = 3.7546, b = 0.3416	2	1742.4	0.001	2
Logistic	0.484	2.612	a = 16.5845, b = 0.0524, c = 11.1117	3	1759.2	0.001	3
Polynomial (Quadratic)	0.478	2.627	a = 6.3821, b = 0.2131, c = -0.00103	3	1769.6	0.001	4
Linear	0.444	2.712	a = 8.1951, b = 0.1141	2	1825.8	0.001	5
Weibull	0.000	3.635	a = 12.5186, b = 23.2525, c = 17.9698	3	2362.7	0.001	6
Exponential	-6.2e+47	9.06e+47	a = 4.37e-16, b = 1.0	2	201,641.6	0.001	Worst

Note: RMSE = Root Mean Square Error; k = number of estimated parameters (coefficients); AIC = Akaike Information Criterion.

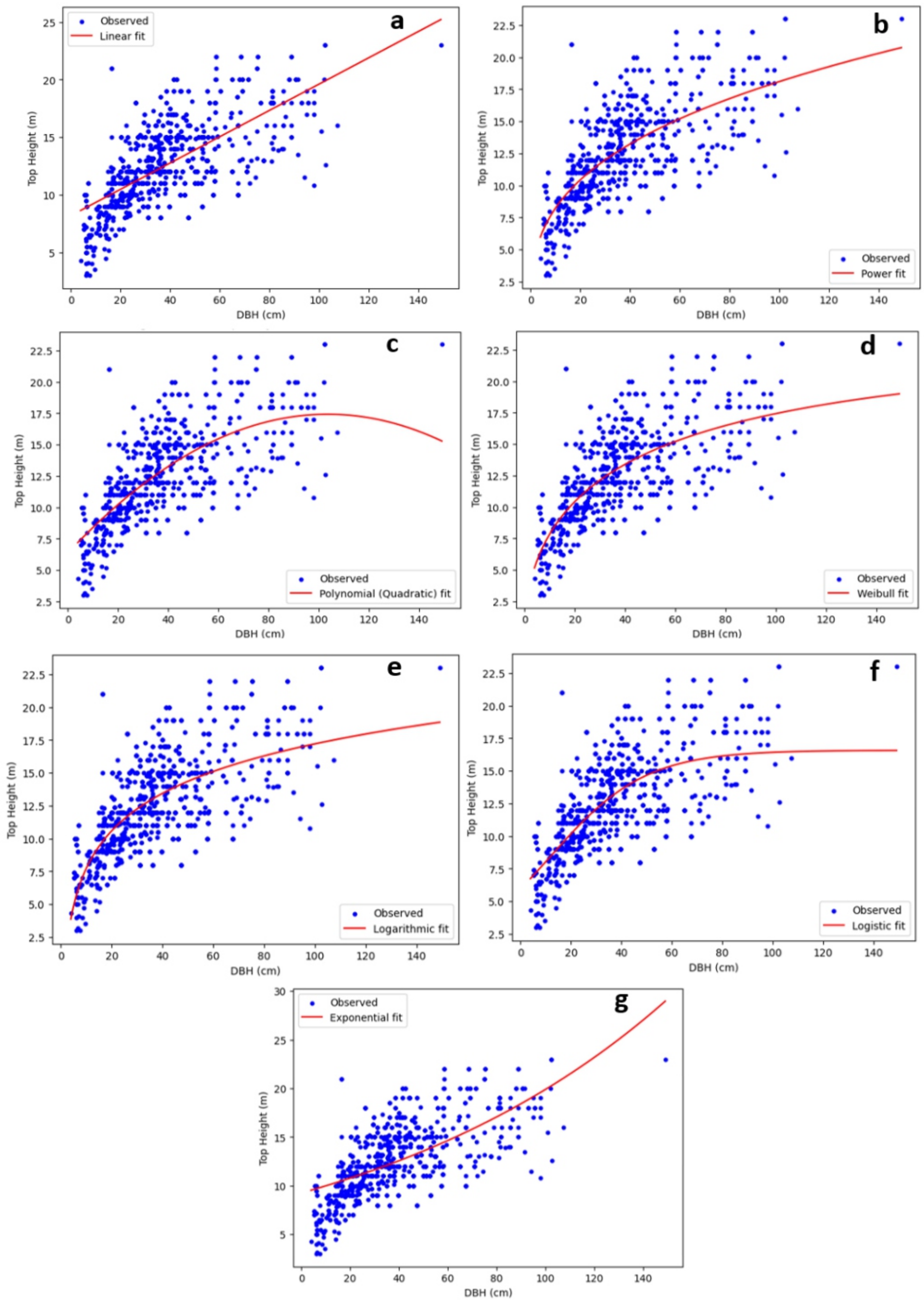

Figure 8. Model of DBH relationship of flooded forest height: (a) linear model, (b) logarithmic model, (c) power model, (d) exponential model, (e) polynomial model, (f) logistic model, and (g) Weibull model.

Table 4. Performance of Stump–DBH regression models in Cambodian flooded forest.

Model	Equation (parameters)	R^2	RMSE (cm)	AIC
Power	DBH=0.969 * Stump Diameter^0.983	0.9661	4.170	672.2
Linear	DBH=0.460+0.895 * Stump Diameter	0.9660	4.178	673.1
Exponential	DBH=19.051* exp(0.0159 * Stump Diameter)	0.9020	7.092	920.8
Logarithmic	DBH=–92.218+36.492* ln(Stump Diameter)	0.8617	8.426	1001.4

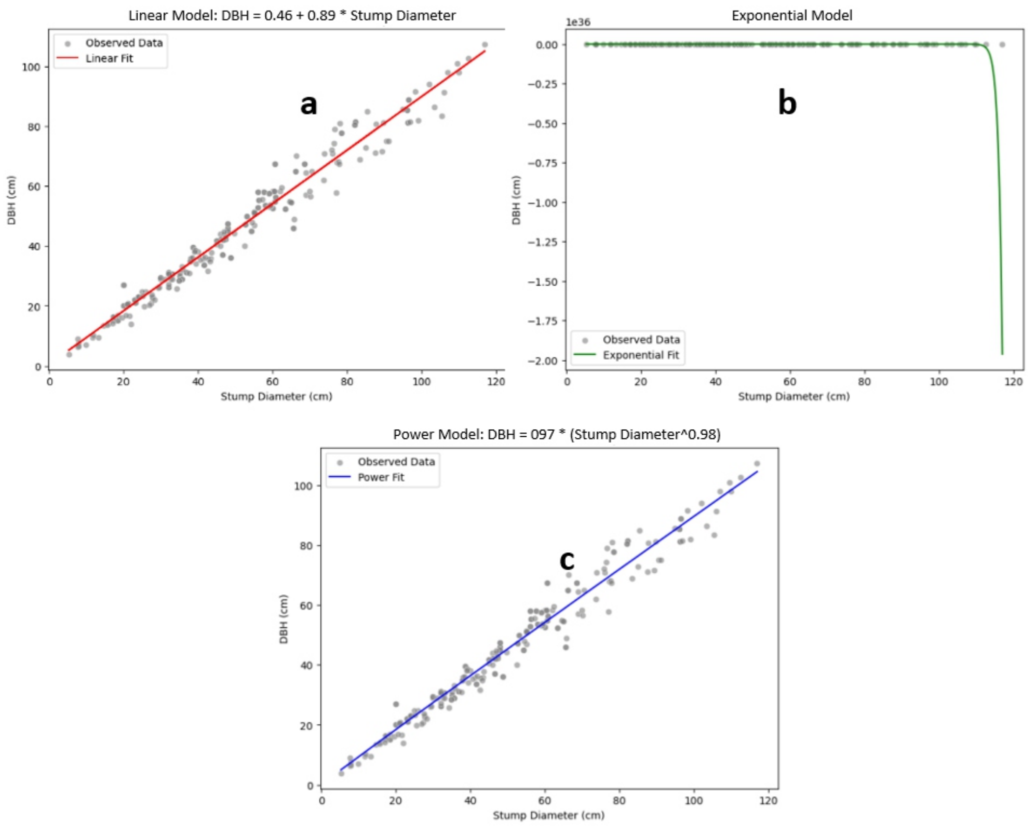

Figure 9. Graph of Stump–DBH regression models in Cambodian flooded forest: (a) linear model, (b) exponential model, and (c) power model.

tool for improving forest inventories and ecological modeling in flood-adapted ecosystems in Southeast Asia.

Stump–DBH Model Development and Fitting

This study tested four regression models, including linear, power, exponential, and logarithmic functions, to predict diameter DBH from stem diameter in a flooded forest of Cambodia (Figure 9a–c; Table 4). Based on the results, the power model provided the best results, with the highest coefficient of determination (R^2=0.9661), the lowest prediction error (RMSE=4.17 cm), and the smallest Akaike information criterion (AIC=672.2). The linear model also produced almost the same results (R^2=0.9660; RMSE=4.18 cm; AIC=673.1), and a ΔAIC value of less than 2 showed statistical equivalence to the power model. The exponential and logarithmic models performed less well, with lower R^2 values (0.9020 and 0.8617, respectively) and higher RMSE values, showing a poor fit to the observed data. Visual inspection of the fitted curves (Figure 8) confirmed that both the power and linear functions closely followed the observed relationship between stem diameter and DBH, showing an approximately 1:1 correspondence across the full-size range. In comparison, the exponential and logarithmic models deviated significantly at larger stem diameters, producing unrealistic predictions. The strong linearity between stem diameter and DBH shows the consistent stump reduction typical of trees in flooded forests, where most individuals develop cylindrical lower stumps to withstand prolonged flooding. The similarity in performance between the power and linear models suggests that simple linear equations are sufficient for practical field use, providing a valid and easily interpreted method for estimating DBH from stem measurements. Previous studies reported comparative results in tropical and riparian forests, where stump-based models were reliable for estimating post-harvest biomass and forest inventories when standing trees are not available (Chadwick et al. 2025). Both models showed high predictive accuracy, but the power model offered slightly higher flexibility in representing proportional growth, serving as the preferred model for converting stem diameter to DBH in assessing biomass and carbon stocks of Cambodian flooded forests. Both power and linear models showed minimal prediction bias and low RMSEP values during independent validation, confirming suitability for reconstructing DBH from stump diameter.

Best Model Selection

The power model (DBH=0.969 × Stump Diameter^0.983) provided the best performing equation for predicting DBH from stump diameter in Cambodian flooded forest. This model had the lowest AIC value (672.2), the highest R^2 coefficient (0.9661), and the lowest RMSE (4.17 cm), showing high predictive accuracy and good performance of the model. The coefficient value (0.983), close to 1, showed an approximately perfect symmetrical relationship between stump diameter and DBH, consistent with the typical cylindrical shape of trees well adapted to flooded conditions. Although the power model performed best, the linear model (DBH=0.460 + 0.895 × Stump Diameter) showed similar same results (ΔAIC < 2), indicating statistical equivalence between the two models. Due to the simplicity and ease of field application, the linear equation serves as an effective alternative when there are limited computational resources or data accuracy. The high correlation and small variation between stump diameter and DBH show that both models accurately describe stem taper patterns. These models can also support post-harvest assessment, mass estimation, and carbon stock calculation in Cambodian flooded forest ecosystems (Rex et al. 2020; Koreň et al. 2024). Despite strong predictive performance, the models represent average relationships across species, and species-specific or hierarchical modeling may further reduce uncertainty in future studies.

Conclusion

In conclusion, this study develops and validates a species-independent allometric model to estimate tree height from DBH and estimate DBH from stump diameter in a flooded forest in Cambodia. For the height–DBH relationship, the logarithmic model provides the most accurate result, showing a pattern of rapid height increase at small diameters followed by a plateau at large size. In estimating DBH from stump diameter, both the power and linear models perform well, with the power model showing a slight advantage, consistent with the allometric principles of growth. These results show the need to develop regionally appropriate allometric equations, as global or tropical models cannot capture the unique structural features of trees adapted to submergence. By incorporating equations for estimating height and DBH from tree stumps, the method provides a precise and practical tool for forest inventory, total biomass estimation, and carbon sequestration calculations, particularly in difficult-to-measure areas, such as post-logging or regularly flooded forests. Overall, the developed model improves the accuracy of total biomass estimation and carbon sequestration, providing an important basis for sustainable forest management, ecosystem conservation, and REDD+ implementation in Cambodia's flooded forests. However, this study has several limitations. The models were developed using data from a limited number of plots within a specific flooded forest ecosystem, which may restrict their applicability to other forest types or regions. In addition, species-specific variation and environmental factors (soil conditions and flooding regimes) were not explicitly incorporated into the models. Future research should focus on expanding the dataset across broader geographic areas and forest conditions, integrating species-specific and environmental variables, and validating the models using independent datasets. This would further improve the robustness and generalizability of allometric equations for forest biomass and carbon stock estimation.

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