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Diameter-Height relationship model for *Shorea assamica* in secondary tropical rainforest, South Borneo

Pandu Wirabuana[1*], Yusanto Nugroho[2], Budi Mulyana[3,4]
[1] *University of Hawai'i at Manoa, Honolulu, USA*
[2] *Universitas Lambung Mangkurat, Banjarbaru, 70714, Indonesia*
[3] *University of Sopron, Sopron, Hungary*
[4] *Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia*
* *Corresponding author: panduwir@hawaii.edu*

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ABSTRACT

Diameter-height relationship model is generally developed to facilitate the quantification of tree height at the individual level. However, the model's reliability principally varies due to the influence of certain factors like site quality and type of species. Thus, a site species-specific model is recommended to support sustainable forest management. This study aims to evaluate the best-fit model for estimating the tree height of *Shorea assamica* in the secondary tropical rainforest, South Borneo. Data from forest inventory consisting of 1,440 tree diameter at breast height (DBH) and height measurements were used to evaluate five alternative models, i.e., Linear, Power, Exponential, Sigmoid, and Gompertz. These data were randomly split into two datasets, i.e., initial model development (1,009 trees) and model validation (431 trees). The model reliability was assessed and ranked using the coefficient of determination (R^2), residual standard error (RSE), akaike information criterion (AIC), mean absolute error (MAE), and root means square error (RMSE). The results of the study obtained an average tree diameter of 42.8 cm with the inverval of 22-99 cm and a mean tree height of 16.6 m with the distribution of 11-31 m. The Power model showed the best fit to explain the relationship model between the diameter and height of the *S. assamica* with an R^2 of 74% and an RMSE of 1.72 m. It indicated Power model could facilitate more efficient tree height estimation of *S. assamica* in the study site.

Keyword: Forest Inventory, Power Model, Reliability, Site Species-Specific, Validation

1. Introduction

Tree height is an important parameter to facilitate the quantification of wood production and biomass accumulation at the individual tree level [1]. It is also helpful as an essential variable for evaluating tree stability [2]. In commercial plantation forests, tree height is commonly used to determine the dominant height required for site index development [3-5]. This parameter can also estimate the number of wood logs sortiment resulting from an individual tree [6]. Although it has multiple functions for forest management, tree height measurement is more difficult to conduct than tree diameter. It requires high cost and is a long time-consuming, particularly in forests with dense vegetation. However, it generally results in lower accuracy due to the canopy overlap between trees [7]. Thus, the top crown position needs to be recognized accurately. To anticipate this constraint, developing a diameter-height relationship model may provide better accuracy of tree height in forest inventory. It can also reduce cost allocation and time consumption for data collection. This model will also support forest managers in estimating more accurate forest productivity and formulating better growth and yield regulation decisions.

Developing diameter-height models has been extensively implemented to support forest management worldwide, primarily in commercial plantation forests like pine, poplar, and eucalyptus [8-10]. Those models are also developed for natural forests in temperate and tropics [11-13]. Interestingly, their accuracy highly varies depending on the type of ecosystems, environmental quality, selected species, and management practice [14-16]. Therefore, the best-fit model for every forest ecosystem may differ and can not be generalized with a single model. For example, the diameter-height model of *Eucalyptus nitens* cannot be reliable in estimating the tree height of *E. pellita*. Similarly, the growth model of *E. pellita* in Sumatra may not accurately quantify the growth of *E. pellita* in Kalimantan. It can happen because there is a site-species interaction that causes different growth behavior of trees. While the development of diameter-height models in the secondary tropical rainforests likely more challenging since the ecosystems consist of diverse tree species with multiple characteristics and they grow in the high environmental gradient. Most trees in this site also have uneven aged with irregular spacing and density. Considering the circumstance, developing a site-species-specific model in facilitating precision forest management is essential.

This study aims to develop the best model for estimating the tree height of *Shorea assamica* in the secondary tropical rainforest, South Borneo. It is a commercial species from the dipterocarp family generally used as raw materials for plywood, veneer, and furniture. This species regenerates naturally in this site and is managed using selective cutting systems. Thereby, the accurate quantification of its timber production is required to calculate annual allowable cutting for maintaining its sustainability. By developing the diameter-height relationship model, we expect to support more efficient forest inventory on this site. It also directly helps to obtain a more accurate dataset of tree height as a fundamental parameter to quantify wood production.

2. Methods

2.1. Study Site

This study was done in the forest concession area managed by PT Aya Yayang Indonesia. It is classified as a secondary tropical rainforest ecosystem and is dominated by vegetation from the dipterocarp family. It is located in Tabalong District, around 270 km from Banjarmasin, the capital city of South Borneo province. It has geographic coordinates in S1°39'−1°40' and E115°29'−115°30' (Figure 1). Hills dominate topography with a 15−40% slope percentage. This site is categorized into a lowland area with an altitude of 225−470 m above sea level. Air humidity is approximately 87.6%, with an annual rainfall of 2,589 mm year^{-1}. The highest rainfall is found in November. Dry periods occur for two months, from July to August. The mean daily temperature is 27.6°C with a minimum of 25.7°C and a maximum of 25.7°C. The soil type predominantly comprises oxisols with high acidity levels and low cation exchange capacity.

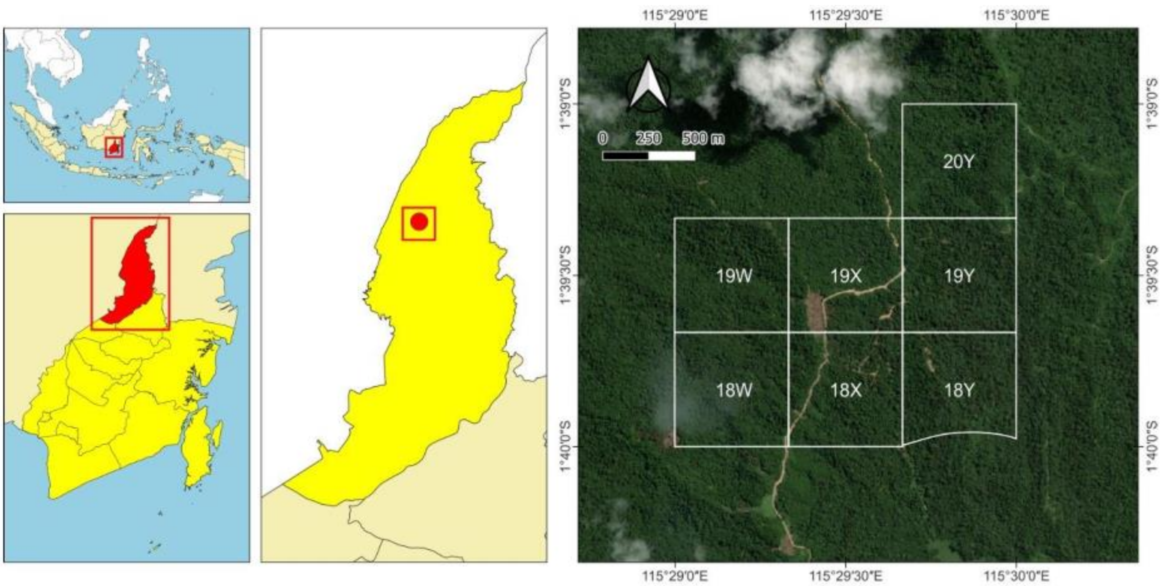

Figure 1. The study location of the secondary tropical rainforest managed by PT Aya Yayang Indonesia in South Borneo [46].

2.2. Data Collection

Seven compartments of the secondary tropical rainforest management unit were selected as the site for data acquisition. The total surveyed area was 700 ha, with every compartment 100 ha. These compartments were categorized into production clusters and managed using selective cutting systems. The scheme was a silviculture approach commonly used in Indonesian natural forests [17-19]. Only trees classified as commercial species could be harvested for timber extraction. The selected compartments were situated close to each other and became the priority area for harvesting activities from 2022−2032.

Forest inventory was undertaken using a census method. Four parameters were recorded from each tree, including botanical name, commercial status, diameter, and height. The commercial status of tree species was divided into two categories, i.e., commercial and non-commercial. To facilitate this process, the dendrologist from the enterprise accompanied the surveyor team during timber cruising. The tree diameter measurement was conducted using a phi band at 1.3 m aboveground. Meanwhile, tree height was measured using a haga altimeter from aboveground to the top crown. The geographic coordinates of each tree were also determined using a global positioning system. Only trees with the limit diameter at least of 20 cm were recorded from the survey following the company's policy regarding timber cruising process.

2.3. Data Analysis

Data screening was done to obtain the dataset of *S. assamica* from the results of forest inventory. The selected dataset was randomly split into two groups, including initial model development and model validation [7, 20, 15]. This study used 70% of the data to evaluate alternative fit models and 30% to test their validity. To recognize the relationship between tree diameter and tree height, a scatter diagram was created to plot both variables. Many studies have used this method to identify the pattern between independent and dependent variables before examining fit models [12, 21-24]. In this context, we arranged tree diameter as X-axis and tree height as Y-axis.

Table 1. Five alternative equations evaluated for diameter-height model of *S. assamica* in secondary tropical rainforest, South Borneo

Model	Equations
Linear	$H = a + b.DBH$
Power	$H = a.DBH^b$
Exponential	$H = a.e^{b.DBH}$
Sigmoid	$H = e^{a+\frac{b}{DBH}}$
Gompertz	$H = a.e^{-b.e^{-c.DBH}}$

Note: *H* was the total tree height (m); *DBH* was the tree diameter at breast height (cm); *a,b,c* were fit coefficients; *e* was the base of the natural algorithm

Five alternative equations were evaluated as candidates' diameter-height relationship models for *S. assamica*, i.e., Linear, Power, Exponential, Sigmoid, and Gompertz (Table 1). These equations were generally used to develop approximate instruments for estimating tree attributes that were difficult to measure [8, 25-27). These five models also offered good fit, reported in the previous literature [10, 28 - 31].

Table 2. Statistic parameters to evaluate the performance of different candidate diameter-height models for *S. assamica*

Statistics Parameter	Equations
Coefficient of determination	$R^2 = 1 - \left(\sum_{i=1}^{n}\left(H_i - \widehat{H}_i\right)^2 / \sum_{i=1}^{n}(H_i - \overline{H})^2\right)$
Residual standard error	$RSE = \sqrt{\frac{1}{n-2}\sum_{i=1}^{n}\left(H_i - \widehat{H}_i\right)^2}$
Akaike information criterion	$AIC = 2k - 2\ln(L)$
Mean absolute bias	$RMSE = \sqrt{\sum_{i=1}^{n}\left(H_i - \widehat{H}_i\right)^2 / n}$
Root mean square error	$MAB = \sum_{i=1}^{n}\left(H_i - \widehat{H}_i\right)^2 / n$

Note: H_i was the observed tree height; $\widehat{H}_i$ was the predicted tree height; $\overline{H}$ was the observed mean tree height; n was the sample size; k was the number of estimated parameters in the model; L was maximized likelihood function for the estimated model; ln was natural logarithm.

Several statistical parameters were used to determine the best-fit model (Table 2). These were coefficient of determination (R^2), residual standard error (RSE), akaike information criterion (AIC), mean absolute error (MAE), and root means square error (RMSE). Rank analysis were also conducted to select the best-fit function. Several studies used this method to support the determination of the best model, primarily when there was not a candidate model which showed outstanding performance of statistical parameters [7, 12, 25]. In this step, these five models were ranked from one to five, one indicating the best for performance criterion. When the values for two or more models were equal, the same rank was given (Mulyana et al., 2020). For R^2, the model had a value closest to the one with the highest rank, while for RSE, AIC, MAB, and RMSE, a value nearest to zero was considered the best (29, 32, 33]. The rank of each model from five parameters was summed up. The model with the lowest sum was selected as the best-fit model [7].

3. Results and Discussion

3.1. Initial Data

A total of 1440 trees data of *S. assamica* were obtained from the result of forest inventory in the study site. The mean tree diameter and height were 37.8 cm and 15.6 m, respectively. For initial model development, 1009 tree height and diameter datasets were utilized, with an average diameter of 38.4 cm and a height of 15.9 m. The total datasets for the validation model were 431 trees with a mean diameter of 47.3 cm and a height of 17.38 m (Table 3). The number of datasets used in this study was higher than another study about diameter-height models of *Shorea sp.* in Borneo with a total of 175 trees dataset [34]. It showed that our study had a sufficient dataset to examine the fit model for estimating the tree height of *S. assamica*.

Table 3. Summary statistics of data for developing diameter-height models of *S. assamica* in secondary tropical rainforest, South Borneo

Statistics	Model Development (70% data)		Model Validation (30% data)	
	DBH (cm)	Height (m)	DBH (cm)	Height (m)
Mean	38.47	15.96	47.32	17.38
Minimum	20.00	11.00	20.00	11.00
Maximum	67.00	28.00	99.00	31.00
Standard deviation	12.98	3.79	20.23	4.58
Standard error	0.41	0.12	0.97	0.22
No. of observation	1009	1009	431	431

Note: *H* was the total tree height (m); *DBH* was the tree diameter at breast height (cm)

The results of the scatter plot demonstrated that there was a positive relationship between tree diameter and height (Figure 2). Tree height generally increased along with the increase in tree diameter. It was also reported in other studies noted a high correlation between tree diameter and height [35 - 37). However, the pattern of the diameter-height relationship between species principally varied even though they indicated a positive trend. Most studies documented that both parameters commonly had a nonlinear relationship [8, 11, 13, 38]. This study also recorded a similar result wherein the scatter diagram between the diameter and height of *S. assamica* indicated a nonlinear pattern

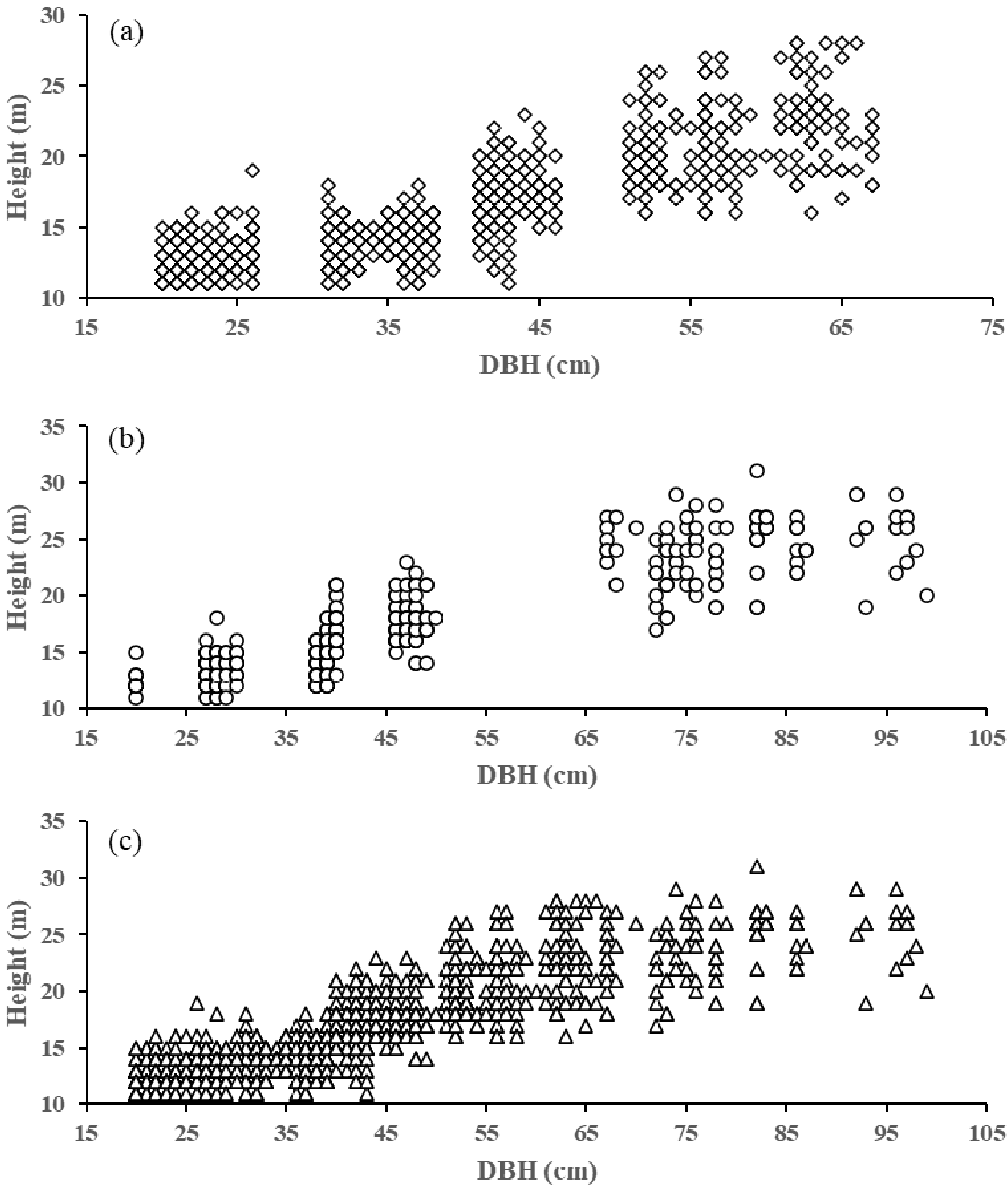

Figure 2. Scatter plot of tree diameter and tree height of *S. assamica* in secondary tropical rainforest, South Borneo: (a) initial model development; (b) model validation; (c) combined data.

3.2. Model Development and Validation

Five alternative models indicated an excellent fit to explain the relationship between the diameter and height of *S. assamica*. The mean variation explained of these five models was 72%, with a minimum of 69% and a maximum of 74% (Table 4). It confirmed that most of the tree height variation of *S. assamica* could be estimated using these models. Our study recorded that the highest R^2 was found in the Power model, followed by the Exponential, Linear, Gompertz, and Sigmoid models. Higher R^2 principally demonstrated better prediction from a model [39]. Several studies reported that R^2 could be stated in decimal or percentage form, wherein a closer value to one or one hundred demonstrated a better fit [7, 40, 41]. However, more than this parameter was needed to assess the model's reliability because the value could change depending on the dataset. The validation test was still required to verify the result using the different datasets from the initial model development.

Table 4. Parameter estimates and performance criteria of five diameter-height models of *S. assamica* in secondary tropical rainforest, South Borneo

Model	Parameters			Performance Criteria				
	a	*b*	*C*	R^2	RSE	AIC	MAB	RMSE
Linear	6.97	0.23	-	0.72	2.91	948.57	1.29	1.75
Power	2.11	0.55	-	0.74	2.97	969.86	1.34	1.72
Exponential	9.09	0.01	-	0.72	3.02	983.65	1.28	1.74
Sigmoid	3.28	-18.89		0.69	3.77	1179.95	1.49	1.94
Gompertz	152.37	0.01	170.49	0.71	2.98	973.33	1.27	1.73

Note: R^2 was the coefficient of determination; RSE was a residual standard error; AIC was the Akaike information criterion; MAB was mean absolute bias; RMSE was the root mean square error

The validation test results found that error for five alternative models varied for each diameter class (Figure 3). In the lower 20 cm DBH class, the Sigmoid model demonstrated the highest over prediction with 1.14 m, while the Exponential model indicated the lowest overestimation with 1.11 m. Interestingly, the Power model had the highest overestimation, with 1.48 m in the 21−30 cm DBH class and 1.64 m in the upper 50 cm DBH class. However, it showed the highest under-prediction with 1.85 m in the 31−40 cm DBH class. For the overall validation dataset, this study noted that the lowest MAE was found in the Gompertz model (1.27), while the lowest RMSE was recorded in the Power Model (1.72). These results could be due to the various observations in each DBH class [7].

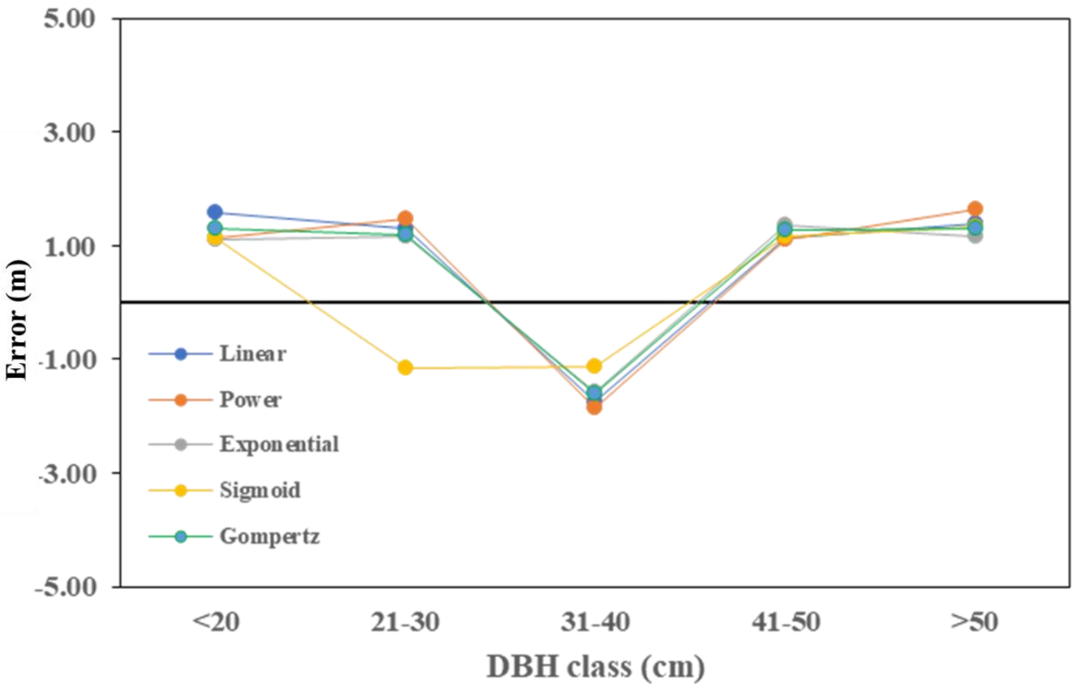

Figure 3. Mean prediction errors in the different tree diameter classes (10 cm intervals) and overall bias for validation of five diameter-height models for *S. assamica* in secondary tropical rainforest, South Borneo.

Considering the performance criteria and rank analysis, the Power Model provided the best-fit model in estimating the tree height of *S. assamica* in the study site, followed by Linier, Gompertz, Exponential, and Sigmoid models. The best-fit mathematical model of the relationship between diameter and height in *S. assamica* is Power model with R^2 of 74% and the lowest RMSE of 1.72 m. This result was contradictive with other studies which reported a sigmoid model as the best-selected model for tree height estimation (8 – 11, 36, 38]. It could be due to the different types of forests and species targeted. Every forest ecosystem has outstanding site quality due to the interaction between soil, climate, and topography [42]. This condition causes a high variation of tree growth between different forest ecosystems. On another side, the genetics of certain tree species also influence their growth behavior, particularly the environmental response [43 - 45]. Therefore, the diameter-height relationship among tree species may differ across various environments.

3.3. Implications Management

Forest inventory is a primary activity supporting sustainable forest management since it provides data and information as baseline considerations in decision-making, mainly related to yield regulation. When faced with secondary tropical rainforest, this activity needs high cost and is time-consuming since it is conducted in an area with hard accessibility. One of the biggest challenges in the forest inventory is to quantify the accurate tree height of the individual tree. The dense canopy provides a more complex situation to recognize the top crown. There is a higher possibility of error in tree height measurement than in tree diameter [11]. It can also cause the overestimation of forest productivity [14] that makes value when determining annual allowable cutting. Measuring tree height in the dense forest also takes time and expensive because there are many trees inside [13].

To anticipate this problem, the availability of a model for tree height estimation is highly required. Besides minimizing error from the measurement activity, this tool can also reduce resource allocation and time consumption since the value of tree height can be determined by using the tree diameter as a predictor. On another side, the diameter-height models for commercial species in the secondary tropical rainforest like *S. assamica* still need to be made available. Therefore, the result can be recommended to support forest inventory in the study site. By having a reasonable tree height estimation, forest managers can determine the precise annual allowable cutting that indirectly reduces the impact of logging on the regeneration capacity of secondary tropical rainforest ecosystems in the study site.

4. Conclusion

Five alternative models indicated good fit to explain the relationship between diameter and height for *S. assamica* in the study area. More than seventy percent of tree height variation could be explained by all models, while the Power model showed the highest R^2 and the lowest RSE, AIC, MAB and RMSE. It indicated that the Power model became the best-fit model to facilitate tree height estimation for *S. assamica* in this location. Therefore, it can be recommended as a tool to support forest inventory in secondary tropical rainforests.

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Conflict of Interest

Authors declare there is no potential conflict of interest for this article

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