

Effect of Local Site Quality Variation on Height-Diameter Allometry of *Pinus patula* at Sao Hill Plantation, Tanzania

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Abstract

This study developed height-diameter (H-D) models that explicitly incorporate site quality for *Pinus patula* in Sao Hill Plantation, in Tanzania, using a large dataset of 42,030 sample trees measured across 976 compartments and 21,355 plots. Site classes were assigned using dominant height-age curves from existing yield tables, resulting in four site-specific datasets used to fit nonlinear H-D equations. Models were estimated using the NLP Procedure in SAS, which calibrated both mean and variance structures to address heteroscedasticity. Model performance was evaluated using AIC, standard error, pseudo-R², and mean prediction error (PE%). Results show that site-class-specific models consistently outperformed the general model, with higher R² (0.63 - 0.74), lower SE (2.76 - 4.21), and non-significant PE% values. Asymptotic H parameters increased progressively from site class IV to I, confirming strong site-level influence on H growth. Validation using independent data demonstrated lower bias for site-specific models across diameter classes and site classes, whereas the general model introduced substantial errors, particularly in poorer sites. These findings highlight the limitations of a unified H-D model and demonstrate that integrating site quality significantly improves H estimations. The study provides site-class-specific H-D models for operational forest inventory, volume estimation, carbon accounting, and growth-and-yield planning in major pine-growing areas in Tanzania, particularly the Southern Highlands.

Keywords

Site Quality, Site Class, Height-Diameter Relationships, *Pinus patula* Plantation

1. Introduction

Forest plantations in Tanzania serve as a pivotal component in fulfilling the nation's timber, poles, pulpwood, and other wood product requirements. Concurrently, these plantations contribute to rural livelihoods, industrial advancement, and climate change mitigation efforts. The establishment of plantations in Tanzania commenced in the 1950s after some years of species and provenance trials, and their expansion has been substantial since then, encompassing an area of 117,000 ha to date (URT, 2022). Plantations were primarily established to ease the growing pressure on natural forests, driven by increasing wood demand associated with population growth. The plantations are dominated by exotic species such as *Pinus patula*, *P. caribaea*, *P. elliottii*, *Cupressus lusitanica*, *Tectona grandis*, and various *Eucalyptus* species. Among these, pines account for over 80% of the total planted area, particularly concentrated in the Southern and Northern Highlands, with Sao Hill Plantation being the most extensive plantation (about 55,000 ha planted) in the southern highlands (Malimbwi et al., 2016; URT, 2022). Management of forest plantations, among other things, requires tools that can predict and estimate yield. Diameter at breast height (D), total tree height (H), and crown diameter are among the primary single-tree parameters needed to estimate forest productivity.

Reliable assessments of forest productivity are essential for sustainable forest management, as they support decisions on annual allowable cuts, rotation periods, and tree species selection (Malimbwi et al., 2016; Splechtn, 2001). Accurate measurement of single-tree parameters H and D is especially important because these variables underpin estimates of tree volume and biomass. Typically, biomass and volume are derived indirectly using allometric equations that employ either D alone or a combination of D and H (Chave et al., 2005). When tree height shows little variation relative to diameter within a stand, equations based solely on D may provide sufficiently reliable volume and biomass estimates. Natural forests, such as Miombo Woodlands, lowland forests, mangroves, and bushland, tend to exhibit greater variation in H relative to D (e.g., Feldpausch et al., 2010; Mugasha et al., 2019). In monoculture plantations where trees are planted at the same time and with the same planting materials, H variations may be considered minimal within a compartment, assuming comparable growth conditions (Bassaco et al., 2018). Nevertheless, this is not always the case, as microenvironmental factors may result in pronounced H variation at a given D (Guzmán-Santiago et al., 2021; Westfall et al., 2017).

On the other hand, since H and D have a strong correlation, H can be estimated from D by applying the H-D equations, since measuring H can be a time-consuming and demanding process (Mehtätalo, 2005; Temesgen et al., 2007). The H-D allometry varies considerably among species, forest types, and sites (Gómez-García et al., 2016; Huang et al., 1992). Consequently, the H-D equations are typically developed for vegetation types (Mugasha et al., 2019), groups of tree species with similar H-D allometry (e.g., Gering & May, 1995), or individual species.

However, as the level of specificity increases from vegetation or group of species level to species level, the accuracy of H estimates from the H-D equation tends to improve.

Consequently, in mono-species plantations, establishing a single H-D equation for a given species is a common practice. However, it is essential to recognize that H-D allometry can vary significantly with site quality or indices (Maguzu et al., 2024; Westfall et al., 2017). Site quality in this case will be denoted as the site index to refer to the measure of productivity expressed as the average H of dominant or co-dominant trees at a specified reference age (Vanclay, 1994). Studies indicate that trees in higher site indices tend to achieve greater H at a given D compared to those in poorer sites (low site indices) (Adeyemi, 2016; Skovsgaard & Vanclay, 2013; Zeide & Vanderschaaf, 2002). This variation necessitates the need to develop site-specific H-D relationships, enhancing the accuracy of H predictions. For instance, a study focused on Scots pine (*Pinus sylvestris* L.) in Bulgaria developed both generalised deterministic and site-specific models to capture the H-D relationship better, accounting for site-specific quality conditions (Stankova & Diéguez-Aranda, 2013). Upon obtaining a more accurate estimation of the H, the dependent variables, including volume and biomass, will also be estimated with adequate accuracy and precision.

In Tanzania, H-D relationship equations that explicitly incorporate site indices have not yet been developed. The few equations that have been considered site indices were primarily designed to determine site quality and to estimate the H of dominant trees, particularly in Pines (Malimbwi, 2016a) and *T. grandis* (Malimbwi, 2016b) plantations. While these models provide useful insights into site productivity, they are limited in application since they focus on dominant trees and are therefore likely to overestimate the H of non-dominant or suppressed trees. Moreover, although separate H-D equations exist for natural forests and plantation systems, they have not integrated site quality into their structure (Mugasha et al., 2019). This omission limits current models' ability to account for site variability, a critical factor influencing tree growth and stand dynamics.

Furthermore, forest management interventions, including silvicultural practices, are typically applied uniformly within a designated management unit, hereafter referred to as a compartment. A compartment constitutes the smallest clearly delineated and relatively homogeneous area within a plantation, established for systematic planning, silvicultural management, and operational record-keeping (Bettinger & Johnson, 2003; Koivuniemi & Korhonen, 2006). Upon reaching rotation age, compartments can be subdivided into harvesting coupes, enabling multiple customers to be allocated specific coupes for harvesting within the same compartment. Estimates of the yield are estimated by using the volume equations developed for *P. patula* that utilise both D and H (Malimbwi et al., 2016). A similar volume equation is applied across the harvesting coupes and compartments. However, local variations in H-D allometry across coupes and compartments may result in either overestimation or underestimation of volume, potentially leading to

inequities whereby some customers or forest managers are disadvantaged while others gain undue advantage. This justifies the agency of having the local H-D that integrates the site quality to mitigate this challenge.

Against this background, the present study aims to develop H-D equations that explicitly incorporate site indices for *P. patula* at Sao Hill Plantation in Tanzania, with the goal of enhancing growth prediction, biomass estimation, and evidence-based plantation management.

2. Materials and Methods

2.1. Site Description

This study was carried out at Sao Hill Forest Plantation, a state-owned and managed by the Tanzania Forest Services Agency (TFS). The Sao Hill is the largest forest plantation with an area of 135,903 ha. However, the planted area is 55,000 ha, of which the *P. patula* occupies about 90% of the planted area. The plantation is located in Iringa region, Southern highland between latitudes 8° 18'S and 8° 33'S and longitudes 35° 6'E to 35° 20'E, at elevations ranging from 1,200 to 2,200 m above sea level (Figure 1). The plantation experiences mean annual temperatures between 6°C and 26°C and annual rainfall ranging from 750 mm to 1,050 mm. Within the plantation, there are patches or a mosaic of lowland forests, particularly on the valley bottoms and adjacent to streams or rivers. Grasslands with scattered trees dominate other adjacent areas of the forest plantation.

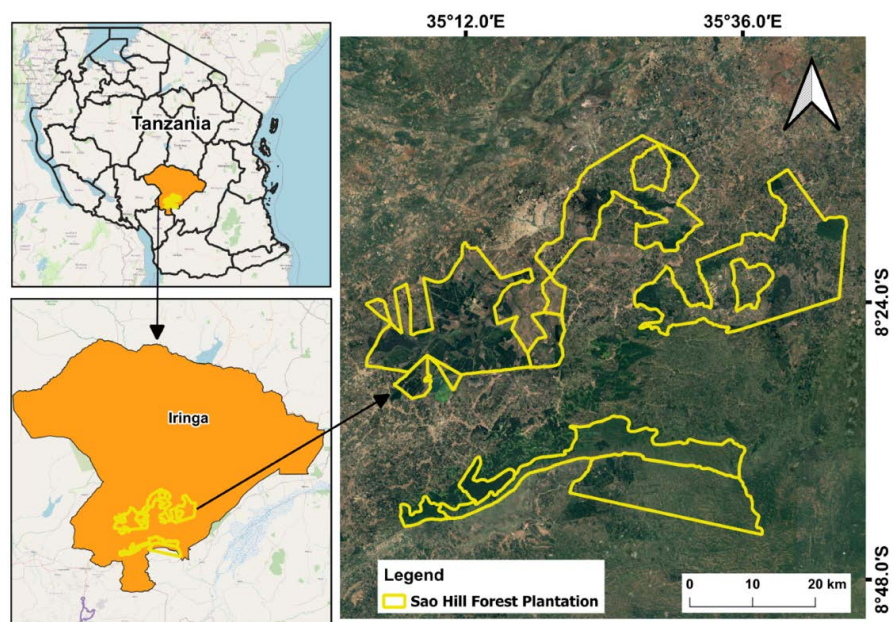


Figure 1. Map showing the location of the Sao Hill Plantation.

2.2. Study Design

This study utilised data that were collected during the forest inventory for the purpose of developing a forest management plan. A systematic sampling design

was applied in each compartment. A compartment is a forest plantation management unit consisting of a single species of trees of the same age. All management practices are conducted simultaneously within a compartment (Bettinger & Johnson, 2003; Koivuniemi & Korhonen, 2006). The sampling intensity was based on age. In compartments with ages from 5 to 12 years, a sampling intensity of 2% was applied, while in compartments with ages above 12 years, a sampling intensity of 5% was applied. The systematic grid with dimensions of 150 m by 100 m and 100 m by 60 m for compartments aged 5 to 12 and above 12, respectively, was applied. The plot's shape was circular with a radius of 9.8 m. In total, 976 compartments planted with Pines were assessed, comprising 21355 plots.

2.3. Data Collection

Inside the plot, plot information such as coordinates, slope, management history (e.g., pruning and thinning), age, and species planted was collected. All the trees within the plot were measured for diameter at breast height (D). In addition, five sample trees were measured for height (H). Of these, three trees with the largest girth were selected to represent the dominant height (HD). Three sample trees were selected in proportion to the plot size of 0.03 ha, based on the standard practice of sampling 100 trees per hectare to represent the HD (Vanclay, 2009). The remaining two trees were chosen to represent the smallest and medium-sized individuals within the stand. Trees with broken tops or deformed trunks were not included in the sample trees selected for H measurement.

2.4. Data Preparation

Data preparation commenced by determining the site class using the information of age and the mean height of the selected tallest trees at the plot level. To identify the site class of each plot within the compartment, the age and mean Dominant Height (HD) information were matched with the site class curves (Equation (1)) available in the developed yield table for Sao Hill Plantation developed by Malimbwi et al. (2016). The yield table presents four site classes, characterized by reference heights (RH) of 12, 17, 22, and 27. The plot was assigned to the site class where the absolute difference between the measured mean HD and the predicted HD by Equation (1) is minimum.

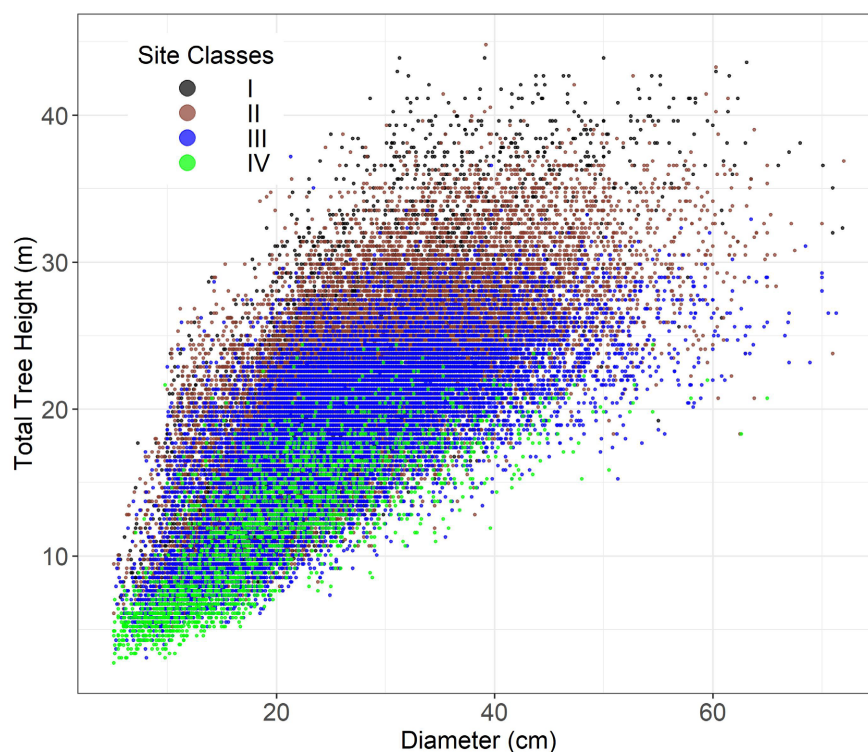
$$HD = 1.564354 * RH * (1 - \exp(-0.092288 * A))^{1.571869} \quad (1)$$

where the RH is the reference tree height, and A is age.

Once the site class of each plot was allocated, at least one tree and up to three trees were measured for H, depending on the number of trees at the plot level that were picked for H-D development. This included one sample tree randomly chosen from the three largest trees, and two sample trees that did not participate in determining the site class, i.e., medium, and the smallest. **Table 1** presents the descriptive statistics summary of sample trees for H-D development for each site class. The scatter plot of the D versus H of each sited class is presented in **Figure 2**.

Table 1. Descriptive summary statistics of modelling data.

Site Class	Sample Trees	Total Tree Height (m)			Diameter (cm)			Age (years)		Dominant Height (m)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Min	Max	Mean
1	6239	5.18	43.89	19.79	5.7	71.0	24.10	6	34	10.02	41.15	20.38
2	22,523	5.18	44.81	20.46	5.1	85.1	26.51	6	34	8.02	35.67	20.87
3	11,522	3.05	37.19	17.65	5.3	74.0	25.49	6	34	5.95	28.45	17.80
4	1746	3.05	24.38	11.58	5.1	72.6	19.46	6	34	3.35	21.14	11.62

**Figure 2.** Scatter plot of total tree height versus diameter for each site class.

2.5. Fitting the Height-Diameter Models

Traditionally, a single general model is fitted for all trees, irrespective of their site quality classes. To evaluate the efficacy of site class models, both site class-specific models and the general model (which integrates all datasets) were fitted to assess the effectiveness of each approach on independent data.

The first step before fitting the H-D models was to select the appropriate H-D equation forms that fit the H-D relationship. Several models describing H-D relationships have been reported (Feldpausch et al., 2010; Mugasha et al., 2019; Westfall et al., 2017). In this study, two widely recognized H-D model forms (Equations (2) and (3)) known for their good fit to forest plantation trees were selected (Richards, 1959; Weibull, 1951). In addition, these models were selected due to their flexibility and their compliance in presenting the biological trajectory of the tree H sigmoid growth, i.e., fast H growth at the beginning and eventually reaching an

asymptote at maturing. In this case, parameter β_0 controls the asymptotic H that the model approaches as D becomes very large; β_1 controls how fast the height approaches the asymptote; shapes the curvature of the H-D relationship by modifying how D influences the growth rate (Saunders & Wagner, 2008; Tanovski et al., 2023).

$$H = 1.3 + \beta_0 * (1 - \exp(-\beta_1 * D^{\beta_2})) \quad (2)$$

$$H = 1.3 + \beta_0 * (1 - \exp(-\beta_1 * D))^{\beta_2} \quad (3)$$

where β 's are the model parameters to be estimated.

Given the large number of observations available per site class, the dataset for each site class was randomly divided into training (80%) and validation (20%) subsets. Random allocation was applied to ensure an unbiased and representative sample of the full diameter range within each site class, thereby avoiding systematic bias in model calibration and evaluation.

Nonlinear Programming (NLP) procedure in SAS (SAS, 2008) was employed to estimate the model parameters (β_0 , β_1 , and β_2). This procedure generates the least squares estimates of the parameters of a nonlinear model through an iterative process. Notably, the procedure simultaneously fits both model and variance parameters (Variance = $a_0 D^{a_1}$; $a_0 + a_1 D^{a_2}$; etc, where "a's" are the variance equation parameters). The variance equation takes care of heteroscedasticity, i.e., an increase in H variations with the increase of D (Figure 2). In addition, the NLP procedure was employed due to its flexibility in modelling the variance equation with varying numbers of parameters and forms, which offer multiple options for determining the optimal model fit. This is in contrast to the *varPower* function implemented in the *nlme* package of R, which is limited to the variance model form of $a_0 D^{a_1}$ (R Core Team, 2025).

2.6. Assessment of Height-Diameter Model's Performance

The best models were selected based on the model performance criteria, i.e., Akaike Information Criteria (AIC) and the Mean Prediction Error percentage (PE%) (Equations (4) and (5)). A paired test was implemented between the observed and predicted values of H to test the significance of PE%. Other models' performance criteria, such as Standard Error (SE) and pseudo coefficient of determination (R^2), were also reported (Equations (6) and (7)).

$$AIC = 2k - 2\ell \quad (4)$$

$$PE\% = 100/n \times \sum_{i=1}^n \left(\frac{H_i - \hat{H}_i}{H_i} \right) \quad (5)$$

$$R^2 = 1 - \left(\frac{\sum (H_i - \hat{H}_i)^2}{\sum (H_i - \bar{H})^2} \right) \quad (6)$$

$$SE = \sqrt{\frac{\sum_{i=1}^n (H_i - \hat{H}_i)^2}{n}} \quad (7)$$

where AIC is Akaike Information Criteria, k is the number of model parameters, ℓ is the value of the log-likelihood, PE% is the mean prediction error percentage, H_i is the observed value of total tree height for observation i , \hat{H}_i is the predicted value of total tree height for observation i , R^2 is the coefficient of determination, and SE is the model standard error.

2.7. Validation of Selected Height-Diameter Models

The selected models were validated using independent data, which comprised 20% of the total observations. This was done by computing the PE% using Equation (5). Both general and site class-specific models were validated. For each of the selected H-D models, the PE% was computed for each site class, the entire dataset, compartment, and plot level, and for diameter classes within each site class. Additionally, visual assessments were performed to identify any potential estimation bias.

3. Results

3.1. Model Performance and Selection

The performance criteria for the fitted H-D models are summarized in **Table 2**. All model coefficients were found to be significantly different from zero ($p < 0.05$). Overall, the two model forms demonstrated consistently good performance across all site classes as well as in the general (combined data) model. The SEs of the estimates were relatively small for site-class-specific models compared to the general model, with SE values ranging from 2.76 to 4.21. Similarly, the R^2 varied between 0.63 and 0.74, with site-specific models generally showing higher explanatory power than the general model. The PE% for all models was not significantly different from zero, ranging from -6.35% to 4.47% . Based on AIC, models 2, 3, 3, and 2 were identified as the best-fitting models for site classes I, II, III, and IV, respectively, while model 2 was selected for the combined dataset (**Table 3**).

Table 2. Performance of the fitted height-diameter models.

Type	Equation#	Model Performance			
		SE	R^2	PE%	AIC
Site Class I	2	4.17	0.68	-5.39	37,800.8
	3	4.21	0.68	-5.41	37,800.9
Site Class II	2	3.92	0.67	-4.47	130,068.7
	3	3.90	0.67	-4.45	130,067.6
Site Class III	2	3.54	0.71	-5.15	64,312.2
	3	3.52	0.71	-5.06	64,307.2
Site Class IV	2	2.76	0.74	-6.34	8834.1
	3	2.75	0.74	-6.35	8837.0
General Equation	2	4.18	0.63	-5.65	248,524.0
	3	4.18	0.63	-5.61	248,527.9

The selected H-D models are presented in **Table 3**. The asymptote (Hmax), representing the maximum attainable tree height with indefinitely increasing D (Bi et al., 2012; Thomas, 1996), varied among models. As anticipated, Hmax increased with higher site quality, i.e., from IV to I (**Figure 3**). The estimated Hmax values for site classes I, II, III, IV, and the general model (all data combined) were 66, 32, 24, 18, and 29 m, respectively. The magnitude of overestimation and underestimation was more evident for the larger trees. The residuals plot (**Figure 4**) did not show any adverse patterns across site classes and for the combined dataset for all selected models.

Table 3. Selected height-diameter models.

Type	Model Expression
Site Class I	$H = 1.3 + 66.6586 * (1 - \exp(-0.0130 * D^{1.2971}))$
Site Class II	$H = 1.3 + 32.3224 * (1 - \exp(-0.0445 * D))^{1.2879}$
Site Class III	$H = 1.3 + 24.6073 * (1 - \exp(-0.0691 * D))^{1.7707}$
Site Class IV	$H = 1.3 + 18.7401 * (1 - \exp(-0.01414 * D^{1.3999}))$
General Equation	$H = 1.3 + 29.1327 * (1 - \exp(-0.0157 * D^{1.2972}))$

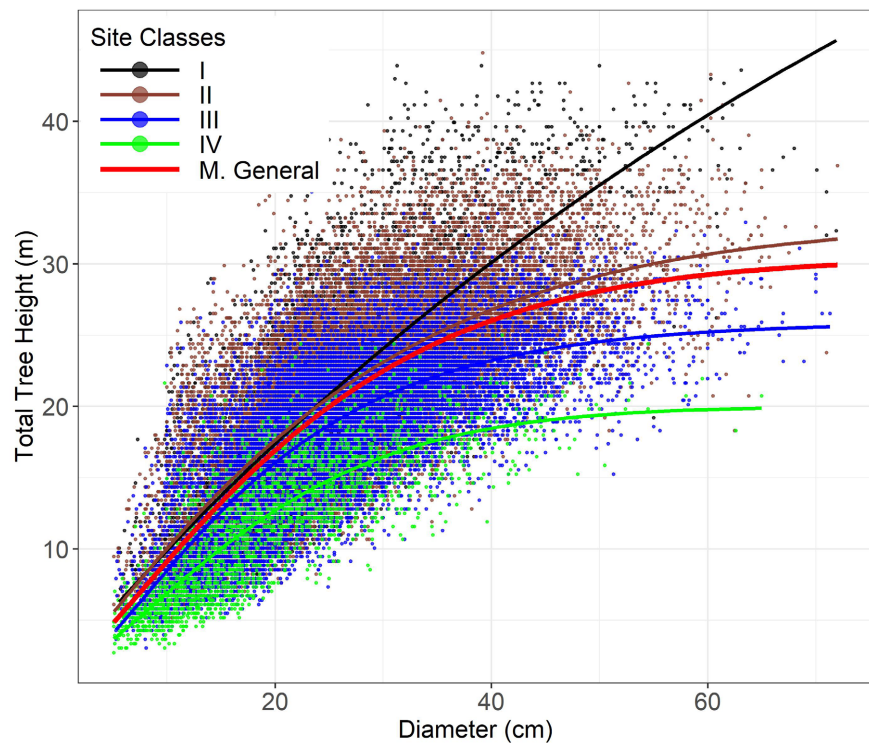


Figure 3. Scatter plots along with the selected model curves for site quality and general models.

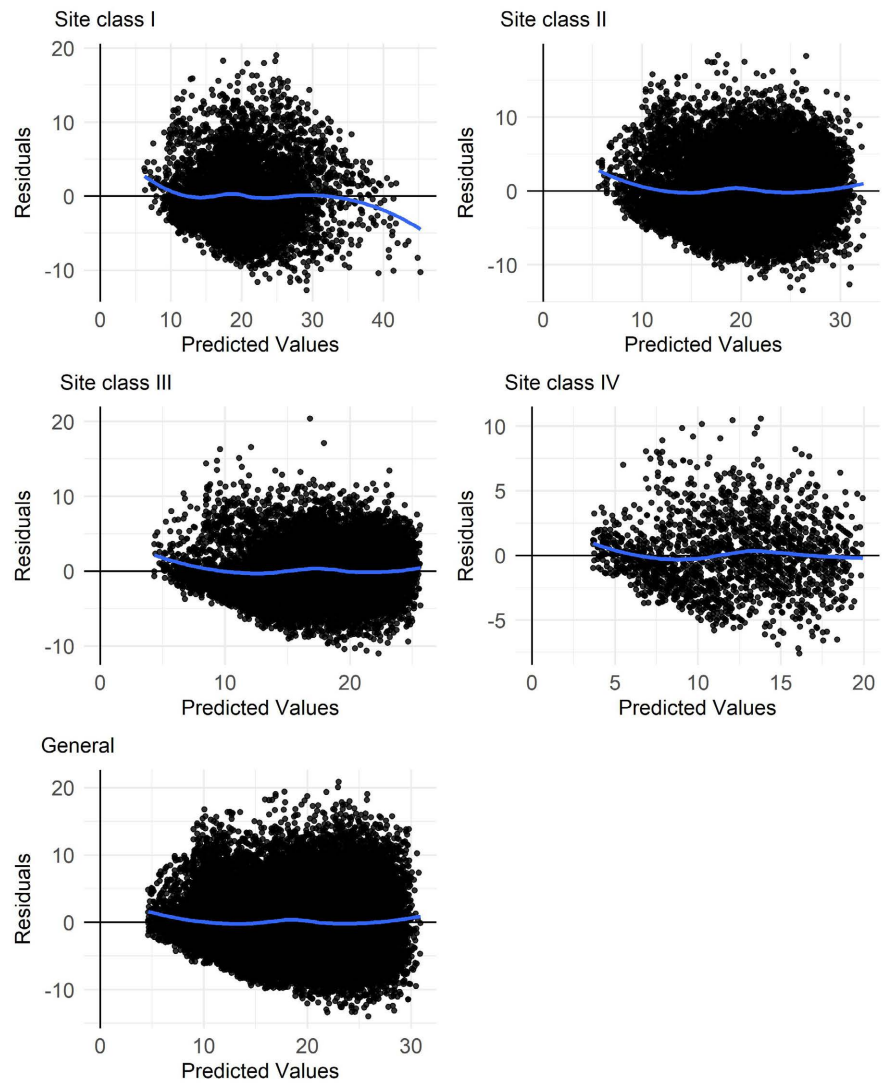


Figure 4. The residual versus predicted values.

3.2. Validation of the Selected Height-Diameter Models

The validation results are presented in **Table 4**. Lower PE% values were observed when the site class-specific values were tested against their corresponding site class data, and the general H-D model when tested on all data combined. When the general H-D model was tested for each site class, the results show that the model performs better for classes I and II and poorly for classes III and IV.

Table 4. Validation results of selected height-diameter models.

Site Classes	Diameter Classes (cm)	Mean Prediction Error (%)	
		Site Class Models	General Model
I	0 - 20	-4.33	-0.45
I	20.1 - 40	-6.07	-0.27
I	>40	-0.37	17.69 ^s

Continued

	Class I	-5.11	0.59
II	0 - 20	-9.59	-3.16
II	20.1 - 40	-2.82	0.34
II	>40	-1.55	1.75
	Class II	-4.22	-0.31
III	0 - 20	-10.28 ^s	-16.39 ^s
III	20.1 - 40	-2.93	-11.18 ^s
III	>40	-2.05	-15.85 ^s
	Class III	-4.95	-13.1 ^s
IV	0 - 20	-5.43	-38.75 ^s
IV	20.1 - 40	-2.54	-39.23 ^s
IV	>40	3.47	-36.50 ^s
	Class IV	-4.07	-38.9 ^s

Note: ^sSignificantly different from zero.

4. Discussion

The H-D relationship equations presented in this study for predicting tree H across different site qualities for pines were derived from an extensive dataset collected from Sao Hill, the largest pine plantation in Tanzania. Data were obtained from all pine compartments, ensuring comprehensive coverage of the full spectrum of H-D allometric variation, particularly that related to differences in site productivity. In total, the dataset included 976 compartments, 21355 sample plots, and 42,030 individual tree observations, representing a substantially larger sample size compared to previously developed H-D models in Tanzania. Earlier studies in the country were generally based on far fewer data points, with sample sizes ranging from 141 to 720 observations in Tanzania (Malimbwi et al., 2016; Mugasha et al., 2019), limiting their ability to capture the full range of structural variability typically found in large-scale plantations. In addition, the present dataset spans a broad distribution of tree sizes, with diameter ranges of 5.7 - 71, 5.1 - 85, 5.3 - 74, and 5.1 - 72.6 cm for site classes I, II, III, and IV, respectively. Including such large-diameter trees is particularly important, as they frequently contribute disproportionately to variation in H-D allometry and exert a strong influence on model behaviour and predictive performance (Chave et al., 2014). By capturing this wide structural and site-quality variation, the present study provides a more robust and representative foundation for developing reliable H-D models for pine plantations in Tanzania.

The analysis revealed that no single model form provided the best fit across all site classes or for the combined dataset, underscoring the importance of evaluating multiple candidate models to identify the one that most accurately represents the underlying data structure. Notably, the explanatory power of the models im-

proved consistently when moving from the general H-D model to the site-class-specific models, as evidenced by higher R^2 values across the stratified formulations. This enhancement in model performance was accompanied by a marked reduction in SE, indicating superior predictive precision and reduced residual variability when models were tailored to individual site classes. The R^2 values obtained in this study are comparable to those reported in earlier research; for example, Zhang et al. (2021) reported an improved model performance, with R^2 values ranging from 0.51 to 0.71, when incorporating site index as a random effect in H-D modelling. Such consistent findings across studies inform that explicitly integrating site quality into model development substantially enhances the overall fit and predictive capacity of H-D models, particularly in forest environments characterised by substantial heterogeneity in site productivity.

As expected, the asymptotic H parameter of the fitted H-D models showed clear and consistent variation across the different site classes, with the asymptote increasing progressively from lower to higher site indices (Figure 3). This trend reflects the fundamental influence of site productivity on height growth, as trees in more favourable environments typically attain greater maximum heights for a given diameter. Moreover, the general H-D model curve was positioned between the curves for site classes I and II and those for classes III and IV, indicating that it does not accurately capture the full range of variation associated with site quality. Specifically, this intermediate placement demonstrates that the general model tends to overestimate tree height in poorer site classes (III and IV), where growth potential is limited, while simultaneously underestimating height in more productive site classes (I and II), where trees grow taller for the same stem diameter. These systematic deviations underscore the strong effect of site class on the development of height for trees with comparable diameters and highlight the limitations of a unified model in representing heterogeneous forest conditions. Such patterns are consistent with findings reported in earlier studies, which emphasise that site quality exerts a significant and measurable influence on H-D relationships and that stratified or site-informed models provide improved accuracy over generalised models (Guzmán-Santiago et al., 2021; Westfall et al., 2017).

The validation results clearly indicate that the site-class-specific models consistently produced lower PE% values than the general H-D model when each was evaluated using independent data, demonstrating superior predictive accuracy under conditions that match their respective site classes. This outcome underscores the critical importance of incorporating site quality into H-D modelling, as tree H growth, crown development, and stem form are strongly influenced by underlying variations in site productivity, soil fertility, moisture availability, and overall stand structure. These ecological and structural differences lead to distinct H-D allometric patterns across site classes, making it unlikely that a single unified model can adequately represent the full spectrum of tree growth conditions. Similar patterns have been reported in the literature, where researchers have highlighted the value of including site-quality surrogates, such as site index, H-D, or

productivity classes, in H-D equations to enhance the reduction in systematic prediction bias. For example, [Krisnawati et al. \(2010\)](#), [Sharma et al. \(2019\)](#), and [Uzoh \(2017\)](#) reported that integrating site quality measures significantly improved the performance of H-D models by better capturing differences in potential H growth among trees of similar D but growing under contrasting site conditions.

On the other hand, when the general H-D model was validated across individual site classes, it performed satisfactorily for high-quality sites (Classes I and II) but exhibited large and statistically significant errors for Classes III and IV. These findings are consistent with earlier research suggesting that general or pooled models often lean toward the characteristics of dominant or highly productive sites, resulting in biased estimates for lower-quality stands (e.g., [Splechtn, 2001](#)). For example, [Duan et al. \(2018\)](#) reported that excluding site-level heterogeneity in H-D modelling forces pooled parameters to reflect the average or dominant site conditions, misrepresenting low-productivity sites.

The site-class-specific H-D models developed in this study provide a practical tool for improving H prediction and subsequent estimation of other important *P. patula* stand parameters such as volume, biomass, and carbon stocks in the Southern Highlands of Tanzania. Given the demonstrated variability in H-D allometry across different site qualities at Sao Hill, the use of a single general model is likely to produce systematic biases overestimating H in low-productivity sites and underestimating it in high-productivity ones. This implies that the use of a site quality-specific H-D model is highly recommended. However, to ensure accurate application, each plot or compartment must first be assigned to its appropriate site class using the DH curves from the Sao Hill pine yield tables ([Malimbwi et al., 2016](#)). By matching stand age and DH with the yield table reference curves, managers can reliably identify the correct site class and apply the corresponding H-D model. This process ensures that H predictions reflect the true site-specific growth potential, thereby improving precision in forest inventories and strengthening decisions related to harvesting, stand valuation, and carbon reporting.

Beyond improving accuracy in routine H estimation, the site-quality-specific H-D models also enhance the reliability of operational and strategic forest management planning. Volume and biomass equations used in Tanzanian plantations typically incorporate both D and H, meaning that improved H prediction directly reduces errors in yield estimation at compartment and coupe levels. This is particularly important at Sao Hill Plantation, where multiple harvesting coupes may exist within a single compartment that are often sold to different buyers. Furthermore, integrating site-specific H-D relationships into growth and yield simulations will support more realistic forecasting of stand development, enabling managers to tailor silvicultural prescriptions, such as thinning regimes, rotation lengths, and harvesting schedules, to the productivity conditions of each site class. Consequently, the adoption of these site-specific H-D models represents a significant advancement toward more precise, site-responsive plantation management in Tanzania's major pine-growing region.

5. Conclusion

This study developed site-class-specific H-D models for *P. patula* at Sao Hill Plantation using a large and representative dataset. The results clearly show that H-D allometry varies substantially with site quality, with higher site classes exhibiting greater asymptotic H. This confirms that site productivity strongly influences H growth for a given D. Across all performance metrics, site-class-specific models provided more accurate and precise H predictions than the general model. They recorded lower SE, higher R², and reduced prediction bias during validation. In contrast, the general model produced significant errors in lower and higher site classes, leading to overestimation of H in poor sites and underestimation in productive ones. These systematic biases highlight the limitations of applying a single H-D model across heterogeneous plantation conditions. This study offers practical H-D models that can be directly applied after assigning each stand to its correct site class using the existing Sao Hill dominant H curves. Using these site-specific models will improve the accuracy of H, volume, and biomass estimation, enhance forest inventory reliability, and support better-informed decisions for harvesting, valuation, and growth and yield planning.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

- Adeyemi, A. A. (2016). Site Quality Assessment and Allometric Models for Tree Species in the Oban Forest, Nigeria. *Journal of Sustainable Forestry*, *35*, 280-298. <https://doi.org/10.1080/10549811.2016.1168306>
- Bassaco, M. V. M., Motta, A. C. V., Pauletti, V., Prior, S. A., Nisgoski, S., & Ferreira, C. F. (2018). Nitrogen, Phosphorus, and Potassium Requirements for Eucalyptus Urograndis Plantations in Southern Brazil. *New Forests*, *49*, 681-697. <https://doi.org/10.1007/s11056-018-9658-0>
- Bettinger, P., & Johnson, K. N. (2003). Spatial Scheduling of Forest Management Activities Using a Dynamic Deterministic Harvest Block Aggregation Process. *Journal of Forest Planning*, *9*, 25-34. https://doi.org/10.20659/jfp.9.1_25
- Bi, H., Fox, J. C., Li, Y., Lei, Y., & Pang, Y. (2012). Evaluation of Nonlinear Equations for Predicting Diameter from Tree Height. *Canadian Journal of Forest Research*, *42*, 789-806. <https://doi.org/10.1139/x2012-019>
- Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D. et al. (2005). Tree Allometry and Improved Estimation of Carbon Stocks and Balance in Tropical Forests. *Oecologia*, *145*, 87-99. <https://doi.org/10.1007/s00442-005-0100-x>
- Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B. C. et al. (2014). Improved Allometric Models to Estimate the Aboveground Biomass of Tropical Trees. *Global Change Biology*, *20*, 3177-3190.

- <https://doi.org/10.1111/gcb.12629>
- Duan, G., Gao, Z., Wang, Q., & Fu, L. (2018). Comparison of Different Height-Diameter Modelling Techniques for Prediction of Site Productivity in Natural Uneven-Aged Pure Stands. *Forests*, 9, Article 63. <https://doi.org/10.3390/f9020063>
- Feldpausch, T. R., Banin, L., Phillips, O. L., Baker, T. R., Lewis, S. L., Quesada, C. A. et al. (2010). Height-Diameter Allometry of Tropical Forest Trees. *Biogeosciences*, 8, 1081-1106. <https://doi.org/10.5194/bg-8-1081-2011>
- Gering, L. R., & May, D. M. (1995). The Relationship of Diameter at Breast Height and Crown Diameter for Four Species Groups in Hardin County, Tennessee. *Southern Journal of Applied Forestry*, 19, 177-181. <https://doi.org/10.1093/sjaf/19.4.177>
- Gómez-García, E., Fonseca, T., Crecente-Campo, F., Almeida, L., Diéguez-Aranda, U., Huang, S. et al. (2016). Height-Diameter Models for Maritime Pine in Portugal: A Comparison of Basic, Generalized and Mixed-Effects Models. *iForest—Biogeosciences and Forestry*, 9, 72-78. <https://doi.org/10.3832/ifer1520-008>
- Guzmán-Santiago, J. C., Aguirre-Calderón, O. A., Vargas-Larreta, B., Gómez-Cárdenas, M., De los Santos-Posadas, H. M., Quiñonez-Barraza, G. et al. (2021). Ecuaciones de calidad de sitio para Abies religiosa en diferentes regiones de México. *Madera y Bosques*, 27, e2732232. <https://doi.org/10.21829/myb.2021.2732232>
- Huang, S., Titus, S. J., & Wiens, D. P. (1992). Comparison of Nonlinear Height-Diameter Functions for Major Alberta Tree Species. *Canadian Journal of Forest Research*, 22, 1297-1304. <https://doi.org/10.1139/x92-172>
- Koivuniemi, J., & Korhonen, K. T. (2006). Inventory by Compartments. In A. Kangas, & M. Maltamo (Eds.), *Forest Inventory* (pp. 271-278). Kluwer Academic Publishers. https://doi.org/10.1007/1-4020-4381-3_16
- Krisnawati, H., Wang, Y., & Ades, P. K. (2010). Generalized Height-Diameter Models for Acacia Mangium Willd. Plantations in South Sumatra. *Indonesian Journal of Forestry Research*, 7, 1-19. <https://doi.org/10.20886/ijfr.2010.7.1.1-19>
- Maguzu, J., Ilstedt, U., Katani, J. Z., & Maliondo, S. S. M. (2024). Variations in the Forest Productivity of *Pinus patula* Plantations in Tanzania: The Need for an Improved Site Classification System. *Forests*, 15, Article 1247. <https://doi.org/10.3390/f15071247>
- Malimbwi, R. E. (2016a). *Development of Yield Tables for Seven Tanzania Forest Service Agency Forest Plantations in Tanzania* (p. 41). Tanzania Forest Services Agency.
- Malimbwi, R. E. (2016b). *Yield Tables for Tectona Grandis at Longuza Forest Plantations* (p. 41). Tanzania Forest Services Agency.
- Malimbwi, R., Zahabu, E., Mugasha, W., & Mauya, E. (2016). *Pinus patula Yield Tables for Sao Hill Forest Plantations. Tanzania Forest Agency Services* (p. 38). Tanzania Forest Services Agency.
- Mehtätalo, L. (2005). Height-Diameter Models for Scots Pine and Birch in Finland. *Silva Fennica*, 39, 55-66. <https://doi.org/10.14214/sf.395>
- Mugasha, W. A., Mauya, E. W., Njana, A. M., Karlsson, K., Malimbwi, R. E., & Ernest, S. (2019). Height-Diameter Allometry for Tree Species in Tanzania Mainland. *International Journal of Forestry Research*, 2019, Article ID: 4832849. <https://doi.org/10.1155/2019/4832849>
- R Core Team (2025). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. <https://www.R-Project.Org/>
- Richards, F. J. (1959). A Flexible Growth Function for Empirical Use. *Journal of Experimental Botany*, 10, 290-301. <https://doi.org/10.1093/jxb/10.2.290>
- SAS (2008). *SAS/STAT User's Guide, Release 9.1. 3*. SAS.

- Saunders, M. R., & Wagner, R. G. (2008). Height-Diameter Models with Random Coefficients and Site Variables for Tree Species of Central Maine. *Annals of Forest Science*, *65*, 203-203. <https://doi.org/10.1051/forest:2007086>
- Sharma, R. P., Vacek, Z., Vacek, S., & Kučera, M. (2019). A Nonlinear Mixed-Effects Height-to-Diameter Ratio Model for Several Tree Species Based on Czech National Forest Inventory Data. *Forests*, *10*, Article 70. <https://doi.org/10.3390/f10010070>
- Skovsgaard, J. P., & Vanclay, J. K. (2013). Forest Site Productivity: A Review of Spatial and Temporal Variability in Natural Site Conditions. *Forestry*, *86*, 305-315. <https://doi.org/10.1093/forestry/cpt010>
- Splechtn, B. E. (2001). Height Growth and Site Index Models for Pacific Silver Fir in Southwestern British Columbia. *Journal of Ecosystems and Management*, *1*, Article 5. <https://doi.org/10.22230/jem.2001v1n1a214>
- Stankova, T. V., & Diéguez-Aranda, U. (2013). Height-Diameter Relationships for Scots Pine Plantations in Bulgaria: Optimal Combination of Model Type and Application. *Annals of Forest Research*, *56*, 149-163. <https://doi.org/10.15287/afr.2013.50>
- Tanovski, V., Matović, B., Risteski, M., & Trajkov, P. (2023). Modelling the Tree Height-Diameter Relationship of Macedonian Pine (*Pinus peuce* Gris.) Forests in North Macedonia. *Journal of Forest Science*, *69*, 497-513. <https://doi.org/10.17221/68/2023-jfs>
- Temesgen, H., Hann, D. W., & Monleon, V. J. (2007). Regional Height-Diameter Equations for Major Tree Species of Southwest Oregon. *Western Journal of Applied Forestry*, *22*, 213-219. <https://doi.org/10.1093/wjaf/22.3.213>
- Thomas, S. C. (1996). Asymptotic Height as a Predictor of Growth and Allometric Characteristics in Malaysian Rain Forest Trees. *American Journal of Botany*, *83*, 556-566. <https://doi.org/10.1002/j.1537-2197.1996.tb12739.x>
- URT (2022). *Forest Plantation Development Strategy (2022-2055)* (p. 71). Tanzania Forest Services Agency.
- Uzoh, F. (2017). Height-Diameter Model for Managed Even-Aged Stands of Ponderosa Pine for the Western United States Using Hierarchical Nonlinear Mixed-Effects Model. *Australian Journal of Basic and Applied Sciences*, *11*, 69-87.
- Vanclay, J. K. (1994). *Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests* (p. 537). School of Environmental Science and Management Papers.
- Vanclay, J. K. (2009). Tree Diameter, Height and Stocking in Even-Aged Forests. *Annals of Forest Science*, *66*, 702-702. <https://doi.org/10.1051/forest/2009063>
- Weibull, W. (1951). *A Statistical Distribution Function of Wide Applicability*. <https://www.scienceopen.com/document?vid=837d29ea-3c9b-493f-802d-1147147a0fea>
- Westfall, J. A., Hatfield, M. A., Sowers, P. A., & O'Connell, B. M. (2017). Site Index Models for Tree Species in the Northeastern United States. *Forest Science*, *63*, 283-290. <https://doi.org/10.5849/fs-2016-090>
- Zeide, B., & Vanderschaaf, C. (2002). *The Effect of Density on the Height-Diameter Relationship* (pp. 463-466). U.S. Department of Agriculture, Forest Service, Southern Research Station.
- Zhang, X., Fu, L., Sharma, R. P., He, X., Zhang, H., Feng, L. et al. (2021). A Nonlinear Mixed-Effects Height-Diameter Model with Interaction Effects of Stand Density and Site Index for *Larix Olgensis* in Northeast China. *Forests*, *12*, Article 1460. <https://doi.org/10.3390/f12111460>