SLENDERNESS COEFFICIENT MODELING AND TREE STABILITY IN OLUWA FOREST RESERVE, ONDO STATE, NIGERIA

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ABSTRACT
Oluwa Forest Reserve (OFR) is a vital natural ecosystem with diverse tree species. This study screened models, evaluated tree growth characteristics and investigated tree stability using slenderness coefficient (SLC). Using systematic sampling techniques two transects of 500 m long each were laid in the study area with 400 m distance between each transect. Four temporary sample plots (TSP) of size 50 m X 50 m each were laid on the transect lines making a total of Eight TSPs for the study. Data were collected on tree height and diameter at breast height (DBH). All tree species with Dbh ≥ 10cm were enumerated. The relationship between the slenderness coefficient and other tree characteristics was examined to identify potential correlations. The correlation coefficient between SLC and the entire diameter at different positions displays a notable negative and strong relationship (r = -0.381), SLC exhibits positive correlations with tree total height (r = 0.258) and merchantable height (r =0.216), The analysis showed that 48% had a low slenderness coefficient, 36% had a moderate slenderness coefficient, and 16% had a high slenderness coefficient in the study area. SLC models were fitted and evaluated. Model 1 ($98.759e^{-0.011DBH}$) performed best with RMSE value of 3717.866, AIC (3729.788), BIC (27.278) and R^2 (0.147). This was followed by Model 3 ($142.747 - 21.783log(DBH)$) with RMSE, AIC, BIC and R^2 value of 27.320, 3719.083, 3731.005and 0.144 respectively. Findings reveal significant variations in slenderness coefficient among different tree species in the reserve.

Keywords: Diameter at breast height, Oluwa Forest Reserve, Slenderness coefficient, tree height, tree structure and stability.

INTRODUCTION
Around the world, forests are essential for sustaining a variety of ecosystems, offering refuge to flora and fauna, protecting clean water sources, creating recreational areas, and bringing about other significant benefits (Brockerhoff et al., 2017). However, in spite of their critical importance, they face a number of difficulties that could jeopardize their biodiversity, ecological resilience, and general well-being. Natural disasters like wildfires, strong winds, ice and snow events, droughts, insect and pathogen infestations, and the spread of invasive plants can all cause these problems. Simultaneously, human endeavors such as pollution, forest fragmentation, and urbanization can significantly impact forest ecosystems and their stability (Nivert, 2001).

Moreover, a mix of biological and physical elements affect a forest stand's stability. A forest's resilience and capacity to tolerate numerous disturbances are determined by the interplay of these factors. Physical factors include topography, soil quality, and microclimate conditions; biological factors include the variety and health of plant and animal species found in the forest. Assessing and managing the stability and resilience of forests requires an understanding of how these factors interact (Nivert, 2001). But the most promising methods for figuring out tree and stand stability, particularly to wind throw, are those that combine local stand characteristics (like average tree height), site, topography, and windiness features with tree stability characteristics (like slenderness coefficient) (Navratil et al. 1994).

SLC has been identified in multiple studies as the primary factor influencing a tree's stability during wind disturbances (Onilude and Adesoye, 2007; Ige, 2017). According to James (2010), Ezenwenyi and Chukwu (2017), trees with low SLC values typically have longer crown lengths, lower centers of gravity, and more developed root systems, all of which point to greater stability. According to reports by Onilude and Adesoye (2007), Ige (2017), and Oladoye et al. (2020), trees with higher SLC values are therefore more vulnerable to wind damage than trees with lower values. In addition, SLC can be used to assess the health and vigor of trees in addition to serving as a competition variable in models of forest growth, aside from the measurement of stand stability (Temesgen et al., 2005). According to Onilude and Adesoye (2007), Harja et al. (2012), Magruder et al. (2012), Budeanu and Sofletea (2013), the tree slenderness coefficient (SLC) is a dimensionless value that can be calculated by dividing the tree's total height (THT) by its diameter at breast height (DBH). It functions as a gauge of a tree's stability and wind-throw resistance. Stands or trees with SLC values above 99 are susceptible to buckling under their own weight, whereas those with SLC values below 70 are thought to be stable when exposed to wind, according to Ige et al., (2022).

Maintaining slenderness coefficient values within certain ranges has been recommended for different tree species in different regions. Managing tree or stand stability is crucial to mitigating wind damage (Ige, 2017). Nonetheless, knowledge about the degree to which forest stands are more susceptible to wind damage could help forest managers plan management and silvicultural techniques according to the acceptable range of SLC values (Wallentin and Nilsson, 2014). An SLC model is required in order to forecast the SLC for the different species of trees in Oluwa FR. This model is intended to function as a basic requirement and reference point for assessing the stability of stands or trees in tropical forests with respect to wind gusts.

METHODOLOGY

Study Area

The Oluwa Forest Reserve, Ondo State, in the Western part of Nigeria (Fig. 1), was the study site. Its land area was 829 km2, with an undulating topography, mean relative humidity of 80%, elevation of 90 m above sea level, and daily temperature of 25˚C. The study was conducted there in an undulating terrain. The range of annual rainfall is 1700–2200 mm. In the reserves, the dry season runs from December to February, and the rainy season lasts from March to November. According to Udoakpan (2013), the study area's vegetation is a mixed/moist semi-evergreen rainforest. The region's native vegetation is a tropical rainforest with emergent species that have numerous canopies and lianas. The forest is made up of both natural forests and plantations, including *Gmelina arborea* and *Tectona grandis*. The natural forest is 8km^2 comprising varieties of indigenous species which includes *Khaya ivorensis, Milicia excelsa, Afzelia bipindensis, Brachystegia nigerica, Lophira alata, Lovoa trichiliodes, Terminalia ivorensis, Terminalia superba, and Triplochiton scleroxylon*. The majority of the soils are ferruginous tropical, which is typical of the type found in heavily weathered basement complex formations in the south-western Nigerian rainforest. Upper in the sequence, the soils are mature, stony, gravely, red, and well-drained. In the reserves, sandy loam is the predominant topsoil texture (Onyekwelu et al., 2008; Adeduntan, 2009, Adeoti, 2019).

Sampling design and data collection

In the middle of the forest, two transect lines were laid, 400 meters apart. Eight (8) temporary sample plots, each measuring 50 m × 50 m and spaced 100 m apart, were arranged along each transect using a systematic sapling design (Fig 2). The diameter at breast height, diameter at the base, middle, and top for tree species ≥ 10 cm, total and merchantable heights, and these measurements were taken in each plot.

Data processing and analysis

Descriptive statistics and correlation analysis

The data were processed into suitable format for analysis (Table 1). This study also employed a combination of descriptive and inferential statistics to analyze the data. Descriptive statistics, including measures of central tendency (such as mean, median, and mode) and measures of dispersion (such as standard deviation and range), were utilized to summarize the tree growth characteristics. Graphical representations, such as plots and charts, were created to visualize the relationships between variables. To further investigate the relationship between the variables, correlation analysis was conducted using Karl Pearson's product moment coefficient of correlation (Table 1). This statistical method was employed to assess the strength and direction of the relationships between the tree growth variables.

Development of models

Non-linear models were developed and tested for tree slenderness coefficient prediction using nonlinear regression procedure nlstools packages in R. The tree slenderness coefficient models formulated to express slenderness coefficient as a function of tree growth characteristics (Dbh). Forms of models generated are presented in Table 2.

Model Evaluation

Model generated were evaluated with a view to selecting the best estimator for tree slenderness coefficient for the study area. The evaluation was based on graphical and numerical analysis of the residuals and four statistical fit indices listed below were also used to evaluate the model.

Coefficient of Determination (R^2):

The coefficient of determination (R^2) quantifies the amount of variation in the dependent variable that can be explained by the independent variable. Equation (5) was used to calculate the R^2 value. A higher R^2 value indicates a better model, as it indicates a larger proportion of the dependent variable's variation being accounted for by the independent variable.

$$R^2 = 1 - \left(\frac{RSS}{TSS}\right) \qquad \text{Equation (5)}$$

Where R^2 = Coefficient of determination; RSS = Residual Sum of Square; TSS = Total Sum of Square

Root Mean Square Error (RMSE): The root mean square error (RMSE) is a measure of the vertical distance between each data point and its corresponding point on the regression line. The RMSE quantifies the average magnitude of the residuals. In order for a model to be considered the best, it should have the smallest RMSE value, indicating a better fit between the model's predictions and the observed data.

RMSE = $\sqrt{\sum \frac{(Y_i - Y^i)}{n}}$ Equation (6)

Bayesian Information Criterion (BIC):
For a model to be considered valid its BIC must be relatively low.

BIC = $n ln \left(\frac{rss}{n}\right) + \quad Pln$ Equation (7)

Akaike Information Criteria (AIC):
This estimates the amount of information lost by a model thereby estimating the quality of the model. For a model to be considered good fit its AIC value must be relatively low.

AIC = $n ln \left(\frac{rss}{n}\right) + \quad 2p$ Equation (8)

Where SS= Sum square, rss = residual sum square; n = sample size, p = number of model fixed Parameters; Y_i = the observed value and Y^i = the theoretical value predicted by the model.

Model validation
Validating of the model was based on the qualitative assessment of the model outputs compared with the real-world data that are independent of the data used in the model construction. In fitting models in the study, calibration data set, comprising 75% of the total data was utilized to calibrate the model, while the remaining 25% was used for validation purposes. The qualitative assessment of the model outputs against the independent validation data served as the basis for model validation.

RESULTS AND DISCUSSION
Descriptive statistics were generated to summarize the characteristics of tree species in the Oluwa forest Reserve. This included mean, median, and standard deviation values for height, DBH, Diameter at the base, Basal area and volume. The results provided a comprehensive understanding of the structural characteristics of trees in the study area as presented in Table 3. The computed tree slenderness coefficients were analyzed to assess the stability of trees in the Oluwa Forest Reserve Stand. The relationship between the slenderness coefficient and other tree characteristics was examined to identify potential correlations. Table 4 presents the correlation matrix, revealing the relationship between SLC and various tree variables. The correlation coefficient between SLC and the entire diameter at different positions displays a notable negative and strong relationship.
Among these variables, DBH stands out with the highest negative correlation coefficient (r = -0.381), indicating that DBH serves as a more reliable predictor of the slenderness coefficient. Additionally, SLC exhibits positive correlations with tree total height (r = 0.258) and merchantable height (r =0.216), while displaying significant negative correlations with Dt (r = -0.363), Dm (r = -0.348), and Db (r = -0.363). However, Figure 3 shows the classification of the SLC into three categories: High, Moderate and Low Slenderness coefficient. Trees with a slenderness coefficient greater than 99 are classified as having a high slenderness coefficient which is prone to wind throw, trees with a slenderness coefficient ranging from 70 to 99 are classified as having a moderate slenderness coefficient and this implies that they can withstand wind throw, and trees with a slenderness coefficient lower than 70 are classified as having a low slenderness coefficient and they can as well withstand wind throw.
The analysis showed that 253 out of the total trees, had a low slenderness coefficient, 190 had a moderate slenderness coefficient, and 81 had a high slenderness coefficient. The classification of tree slenderness coefficients revealed that about half of the trees measured in the study area had a low slenderness coefficient, while 36% had a moderate slenderness coefficient. Additionally, approximately 16% of the trees belonged to the high slenderness coefficient category. This indicates that the trees in the area have a low vulnerability to wind-throw and damage. The classification of Tree Slenderness Coefficient (SLC) in this study followed the result proposed by Navrtatil *et al.* (1994), which categorized SLC into high, moderate, and low classes. Interestingly, the results of this study contrast with those reported by Aghimien *et al.* (2016), who found that 98.8% of the trees in the study area had a low SLC. It was observed that a larger percentage of trees in this area can withstand wind throw.
Five candidate models were chosen for predicting the Tree Slenderness Coefficient (SLC), with diameter at breast height (dbh) being the primary predictor. This choice was made because dbh displayed the highest correlation coefficient, and in practical terms, it is the easiest variable to measure. All of these models demonstrated a robust fit to the data on tree slenderness coefficients. The observed goodness of fit for these models aligns with previous research on the relationship between tree slenderness coefficients and tree or stand characteristics, as documented in works by Orzel (2007), Orzel and Socha (1999), Wang (1998), and Eguakun and Oyebade (2015). To determine the best model explaining this relationship, we employed the criteria of having the lowest values of AICC (Akaike Information Criterion corrected for small sample sizes) and standard error. According to these criteria, the modified exponential model was identified as the most suitable among the candidate models. Consequently, we recommend using this model for predicting the slenderness coefficient within the stand.
The tree slenderness coefficient models were fitted and evaluated. Table 5 presents the models used to estimate the slenderness coefficient values, along with their respective parameter estimates. Table 6 displays the fit indices, which indicate that Model 1 and 3 performed the best in predicting the

slenderness coefficient. It had the lowest values of RMSE (Root Mean Square Error), AIC (Akaike Information Criterion), and BIC (Bayesian Information Criterion), and the highest R^2 (Coefficient of Determination) value, with respective values of 3717.866, 3729.788, 27.278, and 0.147. Model 3 closely followed with RMSE, AIC, BIC, and R^2 values of 27.320, 3719.083, 3731.005, and 0.144. Based on these criteria, Model and 3 model was adjudged the best among the candidate models. Hence, this model is therefore recommended for predicting slenderness coefficient of the stand.

CONCLUSION

The slenderness coefficient is a valuable metric for evaluating the stability and mechanical strength of trees in Oluwa Forest Reserve. It offers insights into tree characteristics, such as species diversity, age structure, canopy architecture, and adaptation to environmental factors. By considering the slenderness coefficient in forest management strategies, the conservation efforts in Oluwa Forest Reserve can be enhanced, leading to the sustainable protection of its valuable natural resources.

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Table 1: Estimation of Variables

Eq.	Variables	Formula	References
1	BA	$\frac{\pi D^2}{4}$	Adeoti, 2019
2	Vol	$\pi H \frac{[Db^2+4Dm^2+Dt^2]}{24}$	Adeoti, 2019
3	SLC	$\frac{THT}{DBH}$	Ige, 2017
4	Karl Pearson Correlation	$r = \frac{\sum(X_1-\bar{X})\ (Y_1-\bar{Y})}{\sqrt{\sum(X_1-\bar{X})^2\ \sum(Y_1-\bar{Y})^2}}$	

Note: Eq. is equations, D is diameter at breast height of the tree (cm), and H is the height of the tree (m), BA = Basal area (m^2), V = Volume over bark (m^3), Db = Diameter at the base, Dm = Diameter at the middle, Dt = Diameter at the top and π = 3.142 (constant), SLC is the slenderness coefficient; r = Pearson Correlation Coefficient, n = number of the pairs of the stock, ∑xy = sum of products of the paired stocks, ∑x = sum of the x scores, ∑y= sum of the y scores, $\sum x^2$ = sum of the squared x scores, $\sum y^2$ = sum of the squared y scores

Table 2: list of SLC Model developed

Model No.	Model Name	Model
1	Exponential	$SLC = ae^{bDBH}$
2	Modified Exponential	$SLC = ae^{\frac{b}{DBH}}$
3	Natural logarithm	$SLC = a + b\log(DBH)$
4	Power	$SLC = aDBH^b$
5	Modified Power	$SLC = ab^{DBH}$

Note: Where: SLC= tree slenderness coefficient; DBH= Diameter at Breast Height; a and b are the regression parameters

Table 3: Statistical summary of the tree growth characteristics

Variables	*DBH(cm)*	*THt(m)*	*Db(m)*	*BA(m^2)*	*Vol(m^3)*	*SLC*
Mean	24.680	16.884	0.292	0.069	0.403	75.500
Standard Error	0.71	0.38	0.01	0.01	0.03	1.24
Minimum	10	4.3	0.102	0.007855	0.041511	10.27
Maximum	118.5	63.7	1.251	1.103019	5.250931	251.69
Sum	12932.4	8847.6	153.18	35.93463	211.1549	39562.05
Count	524	524	524	524	524	524

Note: Where: DBH= Diameter at Breast Height, THt= Tree Total Height, Vol= Volume, BA= Basal Area, SLC= Tree Slenderness Coefficient, Db = Diameter at the base (m)

Table 4: Correlation matrix between slenderness coefficient (SLC) and tree characteristics

Variables	*DBH(cm)*	*THt(m)*	*MHt(m)*	*Db(m)*	*Dt(m)*	*Dm(m)*	*BA(m²)*	*Vol(m³)*	*SLC*
DBH(cm)	1								
THt(m)	0.700	1							
MHt(m)	0.694	0.948	1						
Db(m)	0.985	0.696	0.695	1					
Dt(m)	0.868	0.673	0.695	0.865	1				
Dm(m)	0.937	0.669	0.688	0.930	0.948	1			
BA(m^2)	0.944	0.605	0.603	0.926	0.777	0.865	1		
Vol(m^3)	0.942	0.607	0.611	0.948	0.796	0.878	0.986	1	
SLC	-0.381	0.258	0.216	-0.363	-0.308	-0.348	-0.328	-0.328	1

Note: Where: DBH= Diameter at Breast Height, THt = Tree Total Height, Vol= Volume, BA= Basal Area, SLC= Tree Slenderness Coefficient, MHt = Merchantable height, Db = Diameter at the base, Dm = Diameter at the middle, Dt = Diameter at the top

Table 5: Model Evaluated Parameters

Model No	Model Type	Model Expression	a	b
1	Exponential	$SLC = ae^{bDBH}$	98.759	-0.011
2	Modified Exponential	$SLC = ae^{\frac{b}{DBH}}$	56.401	5.5637
3	Natural logarithm	$SLC = a + b\log(DBH)$	142.747	-21.783
4	Power	$SLC = aDBH^{b}$	183.643	-0.291
5	Modified Power	$SLC = ab^{DBH}$	98.759	0.988

Note: Where a and b are the regression parameters

Table 6: Fit Indices

Model No	*Fitted Models*	AIC	BIC	RMSE	R^2
1	$SLC = 98.759e^{-0.011DBH}$	3717.866	3729.788	27.278	0.146
2	$SLC = 56.401e^{\frac{5.5637}{DBH}}$	3733.104	3745.026	27.812	0.112
3	$SLC = 142.747 - 21.783log(DBH)$	3719.083	3731.005	27.320	0.144
4	$SLC = 183.643DBH^{-0.291}$	3721.539	3733.46	27.405	0.138
5	$SLC = 98.759 * 0.988^{DBH}$	3717.866	3729.788	27.278	0.146

Note: Where: RMSE is the root mean square error, AIC is Akaike Information Criteria and Bayesian Information Criteria (BIC), R^2 is the coefficient of determination

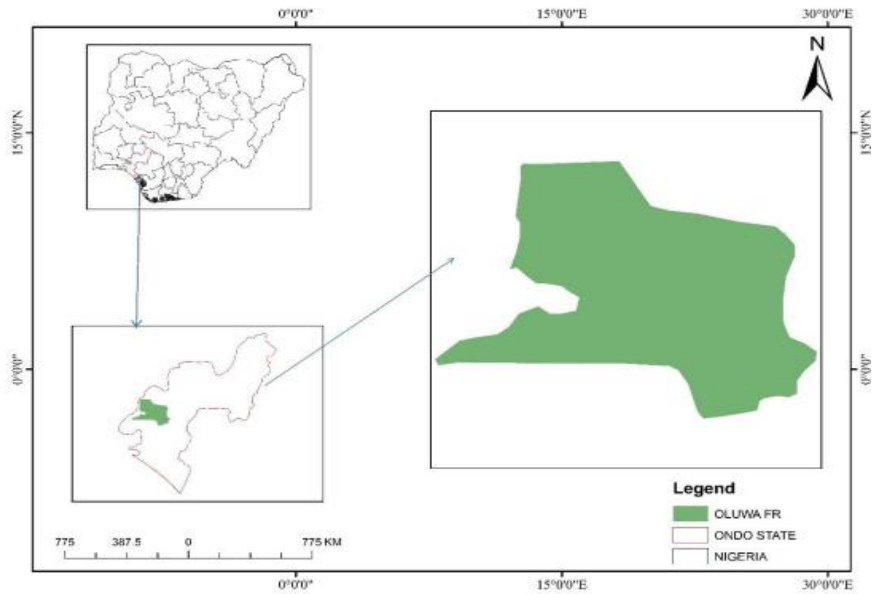

Fig. 1: Study Map of Oluwa Forest Reserve

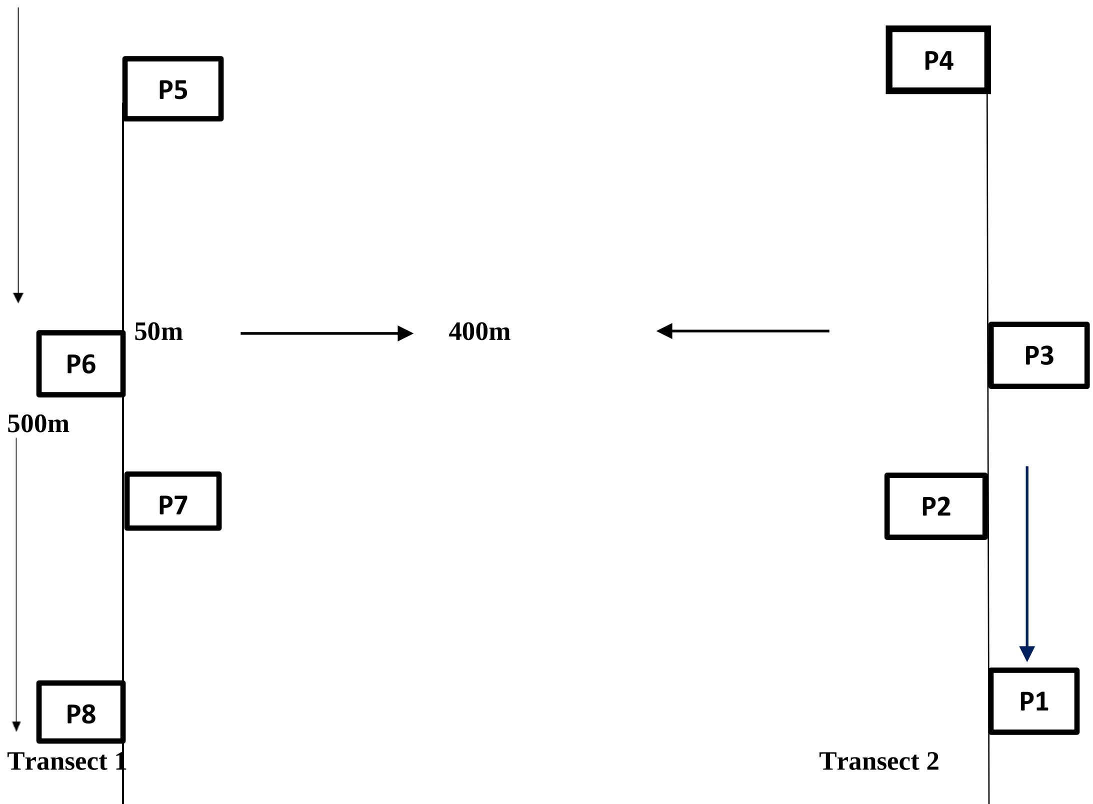

Fig. 2: Line transects for plots layout in Oluwa Forest Reserve

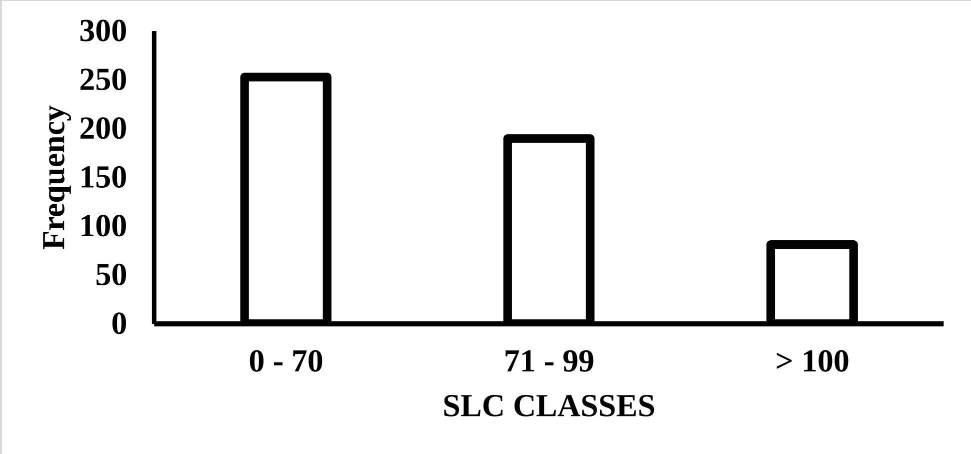

Fig. 3: Slenderness Coefficient Classification

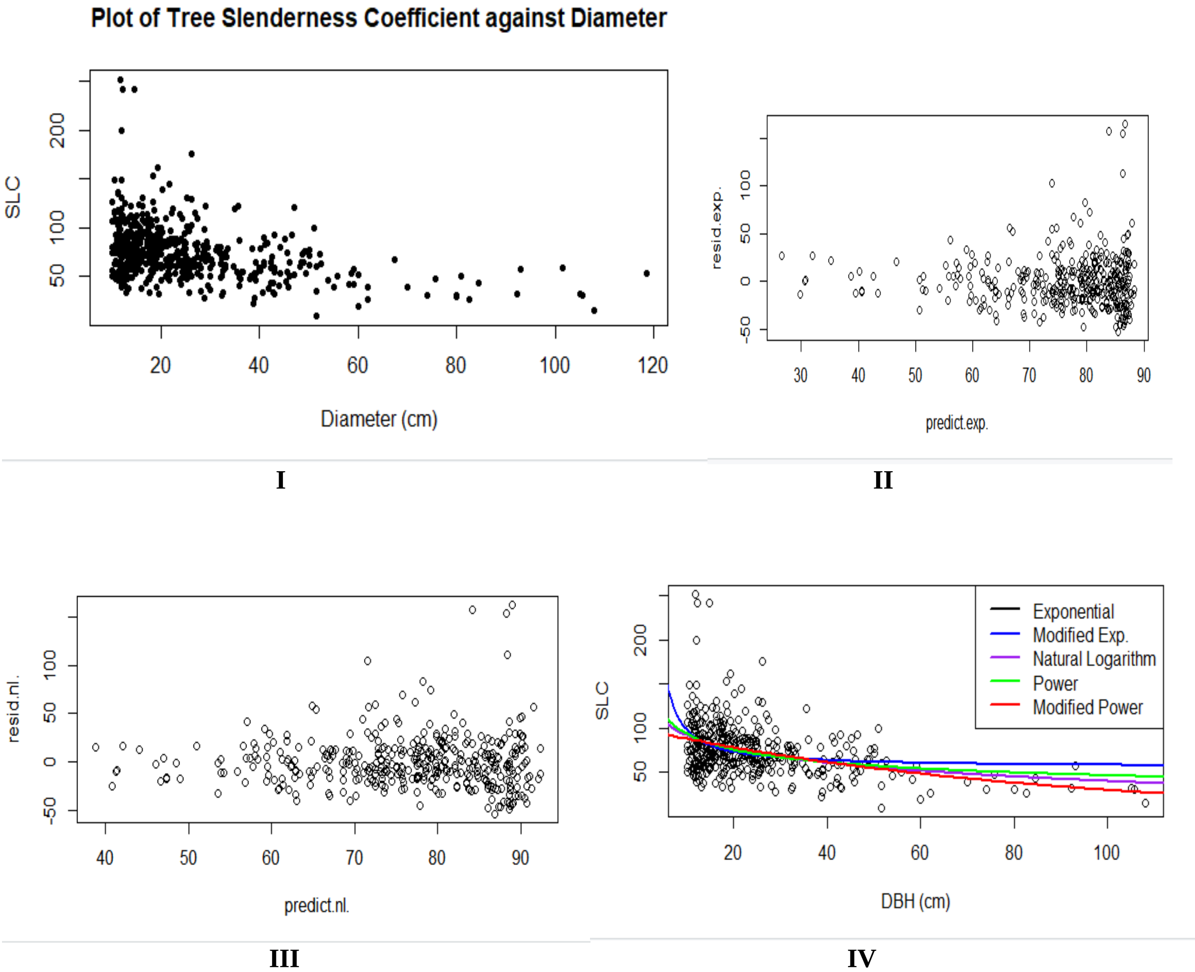

Fig. 4: Plots showing: (I) Relationship between SLC and Diameter at breast, (II) Residual plot for Model 1, (III) Residual Plots for Model 3 and, (IV) Plots for all the Models (I-V)