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Linear and nonlinear slenderness coefficient models for *Pinus caribaea* (Morelet) stands in southwestern Nigeria

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Abstract: *This study evaluated linear and nonlinear slenderness coefficient models for Pinus caribaea* ***as*** *predictive models in Nigeria. Data from temporary sample plots (TSPs) were fitted to several linear and nonlinearfunctional models were to determine the best predictive slenderness coefficient models.The functional models were evaluated in terms of coefficient of determination (R^2) and standard error of the estimate (SEE). The significance of the estimated parameters was also verified with plot of residuals against predicted to ascertain the goodness of fit of the best models. The multiple linearmodels had the highest R^2 and the least SEE and were therefore recommended for predicting slenderness coefficient in the stands with plausible potentials for enhancing reasonable quantification of the stands' stability.*
Keywords*: Linear, model, nonlinear, slenderness coefficient, wind throws.*

I. Introduction

Forests provide habitat for plants and animals, clean water, places for outdoor recreation, and many other benefits. Irrespective of these benefits, they are subject to multiple threats which can jeopardize their health, ecology, biodiversity, and resources. Such threats can be natural or anthropogenic. Natural disturbances include wildfire, catastrophic wind events, drought, insect infestation, fungal/pathogen outbreaks, and invasive plants. Anthropogenic disturbances include pollution, forest fragmentation, and urbanization. The stability of a stand is mainly affected by biological and physical factors (Nivert, 2001). The physical factors are mainly related to the wind components, the topography and the site properties while the biological factors include the species characteristics. Wind is a natural phenomenon in all forest landscapes and some amount of wind damage to forest stands is normal. Wind damage, sometimes referred to as blow down and is defined as the breaking or uprooting of live trees due to strong winds (Navratil, 1996). Vulnerability of individual trees and stands to wind is based on a combination of tree attributes (species, age, health, total height, crown size, rooting characteristics), stand conditions (species, density, and structure of surrounding stands), local topography, soils (texture, depth, soil moisture level), and predominant wind patterns (Ruel, 2000).

The most promising approaches for determining tree and stand stability to wind throw are those which integrate tree stability characteristics (e.g., slenderness coefficient) with local stand (e.g., average tree height), site, topography, and windiness features (Navratil *et al*.,1994). Wang et al., (1998) stated that susceptibility of a tree to wind damage is principally influenced by the slenderness coefficient or taper of the tree. Slenderness coefficient of a tree is defined as the ratio of total height (H) to diameter outside bark at 1.3 m above ground (DBH) when both H and DBH are measured in the same unit (Wang *et al*., 1998). This coefficient is related to tree taper, and is the inverse of the DBH/Hratio that is often used to measure tree taper over the entire main stem of the tree. A straight relationship exists between the slenderness coefficient of the stands and the risk of stem breakage or tree fall due to abiotic factors such as the wind.

Tree slenderness coefficient often serves as an index of tree stability, or the resistances to wind throw (Navratil, 1996). A low slenderness coefficient value usually indicates a longer crown, lower centre of gravity, and a better developed root system. Therefore, trees with higher slenderness coefficient values (that is slender trees) are much more susceptible to wind damage. Actions improving the stability of trees and stands could considerably limit these damages. Because of tree slenderness coefficient importance for indexing tree resistance to wind throw,it is, therefore, important to get to know slenderness of trees, considered to be a measure of their stability, especially of conifers as well as developing models that can predict this values. The objective of this study is to estimate slenderness coefficient value for *Pinus caribaea* and to develop slenderness coefficient predictive models.

II. Materials And Methods

Study area

The study was carried out Omo Forest Reserve (J4). It is situated between latitude 6^o35^1 and 7^o05^1N and longitudes 4^o19^1 and 4^o40^IE. The Reserve shares its northern boundary with Osun and Ago Owu Forest Reserves in Osun state and Oluwa Forest Reserve in Ondo state. The Omo and Oni Rivers mark the southern boundary. The Oni River continues futher north to form eastern boundary, while the western boundary is formed by surveyed paths and demarcated cut lines. The Reserve had a total area of approximately 130,550ha with 65km of enclaves. Communities present include Aberu, Abititun, Oloji, Osoko, Ajebandele, Abakurudu, Tisaba, Olomogo, Etemi, Abeku. The topography of the reserve is generally undulating with average elevation of 125m above sea level (Akindele and Abayomi, 1993).

Data

Data used for this study was collected from fifteen (15) randomly selected Temporary Sample Plots (TSPs) of size 0.04 ha from three age series. With each TSP, quantitative data such as diameter at breast height (cm), diameter at base (cm), diameter at the middle (cm), total height of tree (m), merchantable height of tree (m) of individual tree were measured.

Model description

Linear and non linear models were developed and tested in this study for tree slenderness coefficient prediction.The tree slenderness coefficient models formulated to express slenderness coefficient as a function of tree growth characteristics.

Computation of derived variables

The data collected from tree measurement was processed into suitable form for statistical analysis. Data processing included basal area estimation, tree slenderness and site index estimation.

Basal Area Estimation

The basal area for each tree in each sample plot was estimated using this formula:

$$BA = \frac{\pi D^2}{4} ------------1)$$

Where BA = Basal Area (m^2), D = DBH, $\pi = 3.143$

Tree Slenderness Estimation

Tree slenderness was estimated for all trees using this formula

$$TS = \frac{H}{D} ----------- (2)$$

Where TS = tree slenderness, H = height, D = DBH

Stem volume estimation

The stem volume for each tree in each sample plot was estimated using the Newton's formula

$$V = \frac{h}{6}\left(A_b + 4A_m + A_t\right) ------(3)$$

Where V = Stem volume (m^3), h = Merchantable height (m), A_b, A_m, A_t,= cross sectional areas at the base, middle and top of the tree respectively (m^2)

Crown variables estimation

Crown projection area for each tree in the plots was estimated using the formula

$$CPA = \frac{\pi(CD^2)}{4} --------------- (4)$$

Where CPA = crown projection area and CD = crown diameter.
Crown ratio was also computed for each tree using the formula

$$CR = \frac{CL}{H} --------------(5)$$

Where CR = crown ratio, CL = crown height and H = total height.

Model evaluation

The models formulated were evaluated with a view of selecting the best estimator for tree crown ratio. The evaluation was based on the following criteria:

* Coefficient of determination (R^2)

$$R^2 = 1 - \left(\frac{RSS}{TSS}\right) ------6)$$

Where R^2 = Coefficient of determination

RSS = Residual Sum of Square
TSS = Total Sum of Square

* Standard error of estimate (SEE)

$$SEE = \sqrt{MSE} ------7)$$

Where SEE = Standard Error of Estimate
MSE = Mean Square Error

In addition, the significance of regression coefficients (t) was observed. Only equations having all the parameters to be significant were selected. A model with high R^2 and low SEE was judged to have good fit. Residuals values were plotted against the predicted crown ratio values to check the constant error assumption.

III. Result And Discussions

The model fitting data set covers a wide range. The minimum, maximum, mean and standard error of main measured and derived variables for the three plantation established year used in the study are presented in Table 1 below.

Table 1: Summary statistics of growth attributes

Growth	1990			1991			1997		
Attribute(s)	Min	Max	Mean ±S.E	Min	Max	Mean ±S.E	Min	Max	Mean ±S.E
DBH(m)	0.24	1.27	0.735±0.017	0.38	1.48	0.819±0.023	0.31	1.06	0.616±0.010
THT(m)	9.00	28.00	19.89±0.347	17.00	26.00	22.04±0.165	14.00	29.50	22.84±0.214
MHT(m)	6.00	23.00	14.90±0.276	12.00	22.00	16.85±0.219	11.00	27.50	19.18±0.246
SQ(m)	4.00	20.00	12.20±0.263	11.00	22.00	16.82±0.208	9.50	26.50	18.77±0.236
CL(m)	2.00	14.00	7.691±0.215	2.00	9.00	5.218±0.133	1.50	17.30	4.066±0.106
CD(m)	1.00	7.80	4.107±0.096	1.50	5.78	3.610±0.091	1.00	7.83	3.712±0.083
BA(m^2)	0.05	1.26	0.453±0.020	0.11	1.72	0.573±0.033	0.08	0.88	0.319±0.010
TSC	12.41	48.91	28.32±0.602	15.38	52.63	28.89±0.695	22.83	64.71	38.64±0.464
VOL(m^3)	0.79	23.84	5.715±0.328	0.95	39.46	8.343±0.569	0.58	19.22	4.669±0.212
CPA(m^2)	0.79	47.79	14.22±0.651	1.77	26.24	10.95±0.506	0.79	48.16	12.22±0.55
CR	0.13	0.72	0.386±0.009	0.10	0.45	0.238±0.006	0.06	0.62	0.182±0.005

DBH(m)- diameter at breast height, THT(m)- total height of tree, MHT(m)- merchantable height of tree, SQ- stem quality, CL- crown length, CD- crown diameter, BA- basal area, TSC- tree slenderness coefficient, VOL- tree volume, CPA- crown projection area and CR- crown ratio

Correlation and Graphical Analysis

In this study effort was directed towards obtaining tree slenderness coefficient prediction models. Before the models were developed,correlation analysis was carried out to give an insightof the association between tree slenderness coefficient and the growthvariables.

Table 2: Correlation matrix between tree slenderness coefficient (TSC) and growth attributes

	TSC	THT	CL	CD	DBH	BA	V	CPA	Age
TSC	1.000								
THT	-0.486*	1.000							
CL	-0.313	-0.003	1.000						
CD	-0.380	0.473	0.203	1.000					
DBH	-0.807*	0.427	0.300	0.555*	1.000				
BA	-0.761*	0.366	0.286	0.503*	0.980*	1.000			
V	-0.618*	0.498	0.238	0.512*	0.906*	0.929*	1.000		
CPA	-0.338	0.448	0.175	0.976*	0.511*	0.467	0.490	1.000	
Age	-0.568*	-0.300	0.553*	0.085	0.359	0.352	0.228	0.048	1

DBH(m)- diameter at breast height, THT(m)- total height of tree, CL- crown length,
CD- crown diameter, BA- basal area, TSC- tree slenderness coefficient, V- tree volume,
CPA- crown projection area and Age series.

The correlation coefficients between tree slenderness coefficients and tree DBH, basal area, volume and age were negative for pine (Table 2). This result indicates that the tree slenderness coefficient values of pine tend to decrease for larger trees, and the largest slenderness coefficient values occur for the trees with small DBH. The correlation coefficients between tree slenderness coefficient and DBH were higher than those correlation coefficients between the other variables. This indicates that tree DBH is a better predictor of the slenderness coefficient than age or volume. The results confirm that the slenderness coefficient generally decreases with increasing stand age. This trend was in agreement with the reports of several authors on the growth attributes and management scenarios for plantation species in Southwest, Nigeria (Onyekwelu, 2001; Onyekwelu*et al*., 2003). Tree height, crown length and crown diameter also showed a negative low correlation with slenderness coefficient.The results of this study were similar with the report of Wang (1998) where the relationship of tree slenderness coefficients and tree characteristics for major species in boreal mixed forests were evaluated using empirical models.

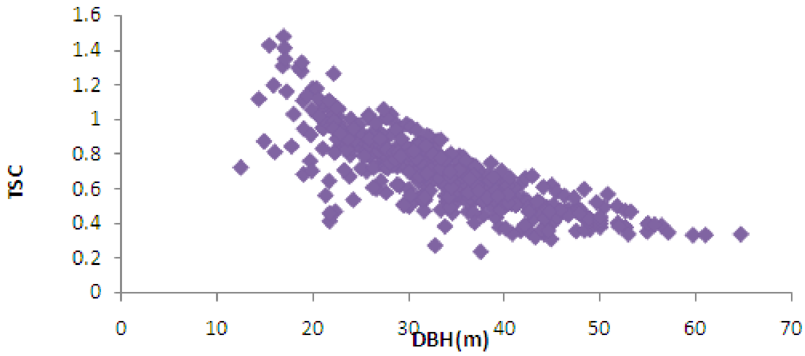

Fig.1: Relationship between TSC and diameter at breast heigh

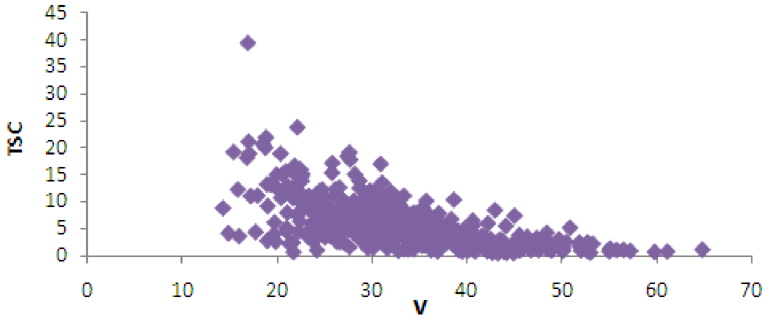

Fig.2: Relationship between TSC and volume

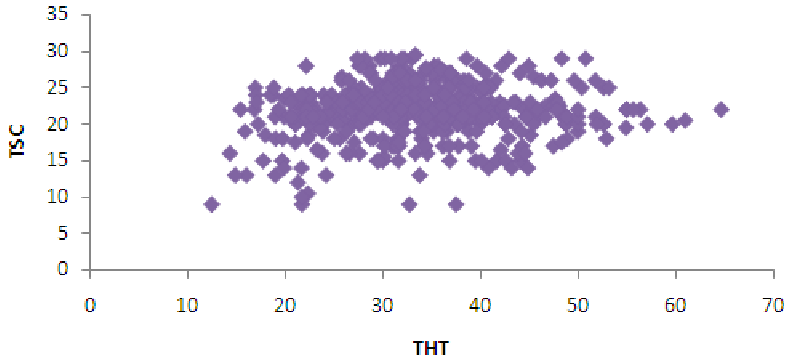

Fig 3: Relationship between TSC and total height

Assuming that a slenderness coefficient value over 100 is considered to be at the high risk of windthrow as suggested by Navratil (1996), the result of this study indicated that the trees of the sampled stands in Omo Forest Reserve do not belongs to the high risk category of windthrow.The relationship of wind throw and slenderness coefficient is indirect. Lower slenderness coefficient can be an indicator of larger crowns, lower centre of gravity and a better developed root system. The desirable height/dbh ratios for adequate wind resistance vary according to species and country. In general, trees with a higher slenderness coefficient (low taper) are much more susceptible to damage than trees with low slenderness coefficient (high taper).Since smaller slenderness coefficient is usually indicating a higher resistance to wind throw, the relationships confirmed suggest that silvicultural treatments, such as producing long-crowned trees, and maintaining appropriate stand density through spacing, thinning, or gradually harvesting overstory trees, can be helpful in reducing the risk of windthrow (Wang *et al*., 1998)

Model fitting and evaluation

Model fitting and evaluation are important parts of model building. Fitting of tree slenderness coefficient models were based on the total data set. A number of different models were examined for predicting tree slenderness coefficient using linear and non linear functions. In this study coefficient of determination (R^2) and standard error of estimate (SEE) were computed in order to evaluate the fitted models. In addition, residual plots were carried out to check the error assumption. The significance of the parameter estimates was also observed. The selected versions of the models arepresented in Table 3.

Table 3: Tree slenderness coefficient models for Pinuscaribaea

Model	Parameter Estimate	R^2	SEE	P value
Simple linear $TSC = b_0 + b_1 DBH$	b_0 = 57.469 b_1 = -34.285	0.651	5.238	0.000
Power $TSC = b_0 DBH^{b_1}$	b_0 = 25.294 b_1 = -0.652	0.641	5.308	0.000
Exponential $TSC = b_0 Exp b_1 DBH$	b_0 = 70.393 b_1 = 1.099	0.671	5.080	0.000
Multiple linear $TSC = b_0 + b_1 DBH + b_2 THT$	b_0 = 35.388 b_1 = -43.810 b_2 = 1.311	0.876	3.120	0.000
Combined variable $TSC = b_0 + b_1 DBH^2 THT$	b_0 = 41.538 b_1 = -0.823	0.372	7.024	0.000
Polynomial $TSC = b_0 + b_1 DBH + b_2 DBH^2$	b_0 = 68.278 b_1 = -65.283 b_2 = 20.384	0.672	5.077	0.000

R^2= coefficient of determination, SEE = Standard error of estimate and P-value = Probability significance.

One unique independent variable thatfeatures in all the models is DBH.Realizing that tree DBH and tree height are the most commonly used variables to predict tree slenderness coefficient (Wang, 1998), they were used in all the models formed. All the models show strong fit to the tree slenderness coefficient data. The observed goodness of fit of the models was in agreement with the previous works on the relationship between tree slenderness coefficient and tree or stand characteristics (Orzeł, 2007; Orzeł and Socha 1999; Wang, 1998). The multiple linear models had the highest R^2 and the least SEE and as such were therefore recommended for predicting slenderness coefficient in the stand.

IV. Conclusion

Diameter at breast height was observed to be common useful independent variable in all the selected models used in the study. Based on the evaluation of the models examined in this study, the multiple linear functions are recommended as tree slenderness models for *Pinuscaribaea*stand in Omo Forest Reserve. These functions have diameter at breast height and height as independent variables. It is noteworthy that the age range of data used for modeling was small. As more data become available to cover a wider range of ages, the models can further be investigated through validation.

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