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MODELING SIZE-DENSITY RELATIONSHIP AND THINNING REGIME FOR THE MANAGEMENT OF *TECTONA GRANDIS* STANDS IN ADO TEAK PLANTATION, EKITI STATE, NIGERIA

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ABSTRACT

Tectona grandis is used for sawn timber, poles, cutting boards, indoor flooring, as a veneer for indoor finishing, medicinal products and shade in Ijan community. Therefore, it is necessary to determine the limits of the possible maximum density the stands can sustain that would lead actions to control competition and growing space. A total of thirty (30) temporary sample plots of 400 m^2 in an even-aged stands of the plantation was laid. Density, quadratic mean diameter, height diameter and volume models were processed and estimated. The results showed that model one (1) of the H-D, model three of the volume and the stochastic frontier half normal (SF HN) model had the lowest selection indices, therefore, were selected as the grand and suitable models for proper management of the plantation. The stochastic frontier half normal (SF HN) model was apt to raise Reineke's model parameters and applied to predict the stand density index. The stand density index allowed the simulation of thinning regime for the stand and suggested the best management strategies to optimize the growing space and the redistribution of growth of the remaining trees. These tools are keys for decision making when proposing cutting intensities in thinnings that prepare the plantation for the final harvest. The thinning regime should be specific for each stand, depending on its quadratic mean diameter and the number of trees per hectare, as well as the type of products to which the trees are to be removed.

Keywords: Competition, density management diagram, stands density index, thinning regime

INTRODUCTION

Tectona grandis is a very important tropical hardwood tree species in Ijan community. Its natural distribution ranges from India to Burma, Laos and Thailand (Hansen *et al*., 2015). The early introductions of teak outside Asia were made in Nigeria in 1902, with the first plantations being of Indian origin and subsequently of Burmese origin. The first pure teak plantation in Tropical America was established in Trinidad in 1913. Teak planting in Honduras, Panama, and Costa Rica started between 1927 and 1929 (Ball *et al.*, 2000). The benefits derived from Teak plantations establishment are majorly on forest products such as sawn timber, poles, medicinal products and shade for agricultural crops (Roland, 2002). Teak's high oil content, high tensile strength and tight grain make it particularly suitable where weather resistance is desired. It is used in the manufacture of outdoor furniture and boat decks. It is also used for cutting boards, indoor flooring, counter tops and as a veneer for indoor finishing. However, despite its economic values and development of great body structures, the comprehensive knowledge of its structural development is not clear. This could be due to the variation in its physiological and morphological traits of the tree species.

The gradual increase in sizes of trees place a great demand on site resources and growing space of the trees species. When the resources are no longer adequate to support all the stand components, self-thinning would be initiated and the number of trees per unit area would decrease. Self-thinning is a fundamental result of highly dynamic competitions and mortality processes (Bi *et al.*, 2000). *Tectona grandis*, like other tree species requires site resources such as light, water, nutrients and space. If resources are inadequate to support full growth potential of all the trees, tree growth would decrease and some trees would die (Burkhart and Tomé, 2012). However, an understanding of the dynamics of tree stands, structured in both size and space, has been limited by lack of models application for forest plantation management (Gratzer *et al*., 2004).

Size density dependent models are management tools that attempt to quantify the interactions and growth of trees in forest plantations. These tools could be applied for the sustainable management of forest plantation in Nigeria, especially in Ijan Teak plantation. In view of the important role of size density in understanding stand dynamics, therefore, this study seeks to model the size-density relationship and thinning regime for the management of Ijan *Tectona grandis* plantation with the specific interest in estimating different height diameter models, esmodels, estimatevolume models, assessing size density models for Reineke model parameters and simulate thinning regimes for the management of *Tectona grandis* in Ijan Teak plantation.

METHODOLOGY

Study Area

Ijan Teak Plantation is located in Ijan community, Gboyin Local Government Area of Ekiti State. It is found in the Northern part of Ekiti State and covers about 391-kilometer squares. It is situated at about 48 kilometres East of Akure, Ondo State capital; 344 kilometres North of Lagos and 750 km South-West of Abuja, the Federal Capital Territory (FCT). Gbonyin is one of the sixteen Local Government Areas in Ekiti State. It lies within Latitude 7°37′00′N of the Equator and Longitudes 5°28′00′ E of the Greenwich Meridian (Adebayo, 1993).

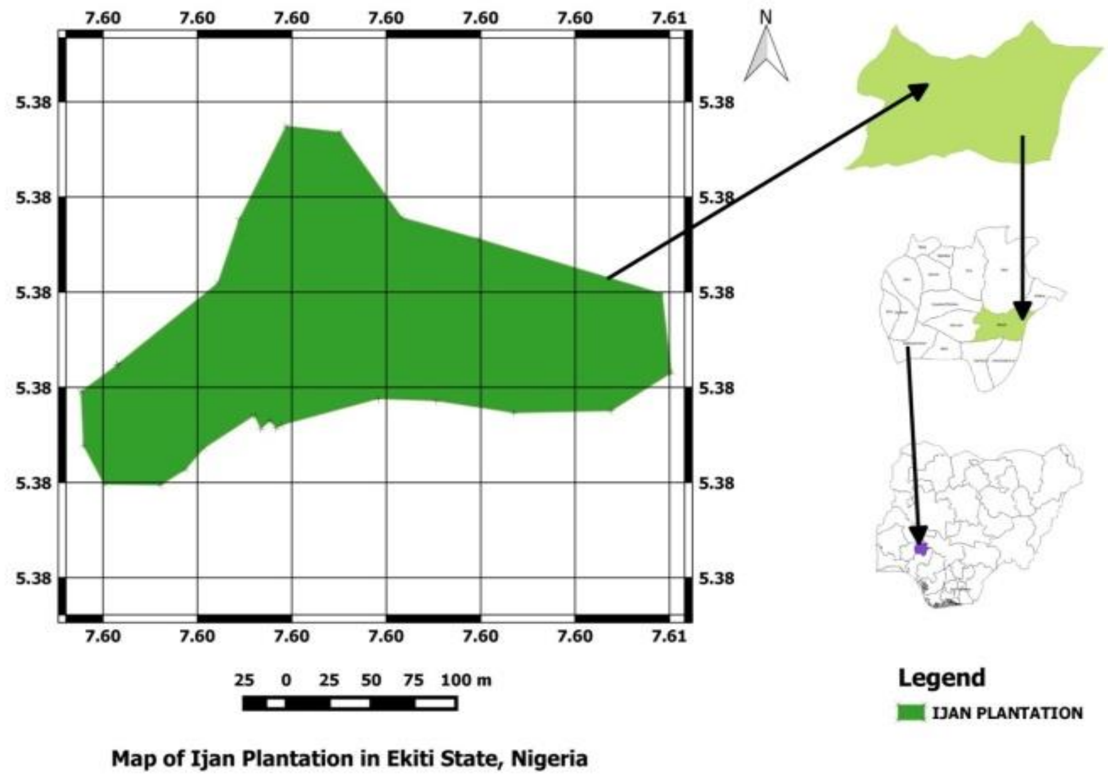


Figure 1: Map of Ijan Teak Plantation

Sampling Techniques

Thirty temporary sample plots of 0.04 ha size was established with 30% sampling intensity. The plots were randomly selected and individual trees within each plot were measured. The diameter at breast height (at 1.3 m above ground level), base, middle and top of trees were measured using a Relaskope. Total heights were measured using Haga altimeter and Global Positioning System (GPS) were used to obtain the reference points of the study area.

Data Processing

The following variables were derived from the measured variables for each individual tree.

Basal Area Estimation

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

Where, BA = Basal area (m^2); D = Diameter at breast height (m); π = constant.

Computation of Stand Volume

$$V = \frac{Ht\,\pi}{24} \times \left(D_b^2 + 4D_m^2 + D_t^2\right) \quad (2)$$

Where V = Volume (m^3); D_b = Diameter at the base (cm), D_m= Diameter at the middle (cm), D_t = Diameter at the top (cm), Ht = Total height (m) and π = constant

Quadratic Mean Diameter

Each plot quadratic mean diameter of trees per hectare was also computed as follows;

$$D_q = \sqrt{\frac{40000}{\pi} \times \frac{BA}{Na}} \quad (3)$$

Where the number of trees = (Na, trees ha^{-1}) and basal area= (BA, $m^2 ha^{-1}$)

Modeling Approach

The maximum density relationship as proposed by Reineke (1933) was based on the number of trees per ha and quadratic mean diameter per ha (in logarithm scale); expressed as:

$$Na = \beta_0 + \beta_1 D_q + \in \quad (4)$$

When natural logarithm is applied to the above equation, the linear form was obtained as follow:

$$LnN_a = \beta_0 + \beta_1 LnD_q + \in \quad (5)$$

Where *Na* = number of trees per ha, *Dq* = quadratic mean diameter, β_0 and β_1 = intercept and slope of the regression model.

To date, different methods have been used to fit self-thinning line for many species. Therefore, four different estimating methods were used to estimate the parameter in Reineke's model and the best method was selected.

Ordinary Least Squares Estimate

$$Y = \alpha + \beta X + \in \quad (6)$$

Where

$$\sum_{i=1}^{n} e^2 = \sum_{i=1}^{n} (y - a - bx)^2 \quad (7)$$

$$\beta = \frac{SS_{xy}}{SS_{xx}}, \qquad \alpha = \bar{y} - \hat{\beta}\,\bar{x} \quad (8)$$

$$\beta = \frac{\sum xy - \frac{(\sum x)(\sum y)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \quad (9)$$

Stochastic Frontier Estimate

$$LnNa = \beta_0 + \beta_1 LnD_q - u + v \quad (10)$$

Where: *Na*= Number of trees β_0 & β_1 = Parameters to be estimated

Dq= Quadratic mean diameter *v* & *-u*= Terms of error in the model

Ln= Natural logarithm

Quantile Regression (QR)

$$\hat{y}_\tau\, Ln(Na) = \beta_0 + \beta_1 LnD_q + \in \quad (11)$$

Where

$\hat{y}_\tau\ Ln(Na)$ is the estimated value of the τth quantile of the number of trees per ha at quadratic mean diameter (Dq), the intercept β_0 and slope β_1

Statistical Evaluation

All methods were fitted in R (R Core Team, 2017).The methods were assessed based on R^2_{adj}, Root Mean Squares Error (RMSE), Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC).The graphical performance of the self-thinning lines from the different methods were assessed by over laying them on the field inventory data.

$$R^2_{Adj} = \frac{(n-1)\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{(n-p)\sum_{i=1}^{n}(y_i-\hat{y}_i)^2} \quad (12)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}{n-p}} \quad (13)$$

$$AIC = -2loglik + 2p \quad (14)$$

$$BIC = -2loglik + pln \quad (15)$$

Where: y_i = the observed Na, $\hat{y}_i$ = predicted Na, $\bar{y}$ = average Na, n = total number of observation that was used to fit the model, p = number of parameters to be estimated, $k = p + 1$

Density Management Index

$$SDI = Na \times \left(\frac{D_{qr}}{D_q}\right)^{\beta_1} \quad (16)$$

And, to obtain the number of trees of a given SDI:

$$Na = SDI \times \left(\frac{D_q}{D_{qr}}\right)^{\beta_1} \quad (17)$$

Where:

Na= Number of trees, *Dq* = Quadratic mean diameter, *Dqr* = Quadratic reference mean diameter

β_1 = Parameters to be estimated

Thinning Simulation

In order to estimate timber possibility, the total height of the trees for each diameter value was estimated with the allometric height-diameter model for *Tectona grandis*

Height was estimated using height allometric model

$$H = \frac{\beta_0 D}{(1+D)^{\beta_1}} \quad (18)$$

$$H = \frac{\beta_1 D}{(\beta_0 + D)} \quad (19)$$

$$H = \beta_0 \times \left(1 - exp(-\beta_1 D)\right) \quad (20)$$

The volume of the total stem over bark (V) was obtained

Volume was also estimated using volume allometric model

$$V = \beta_0 + \beta_1 D^2 H \quad (21)$$

$$V = \beta_0 + \left(1 - exp(-\beta_1 DH)\right)^3 \quad (22)$$

$$= \beta_0 + (\beta_1 DH)^2 \quad (23)$$

Timber Cutting intensity (IC%) was calculated as

$$IC\ \% = \left[\frac{(Na_1 - Na_2)}{Na_1}\right] \times 100 \quad (24)$$

In all the plots, a relative growth space (RS) was calculated:

$$RS = \sqrt{\frac{\left(\frac{10000}{Na}\right)\times 2}{\sqrt{3}}} \quad (25)$$

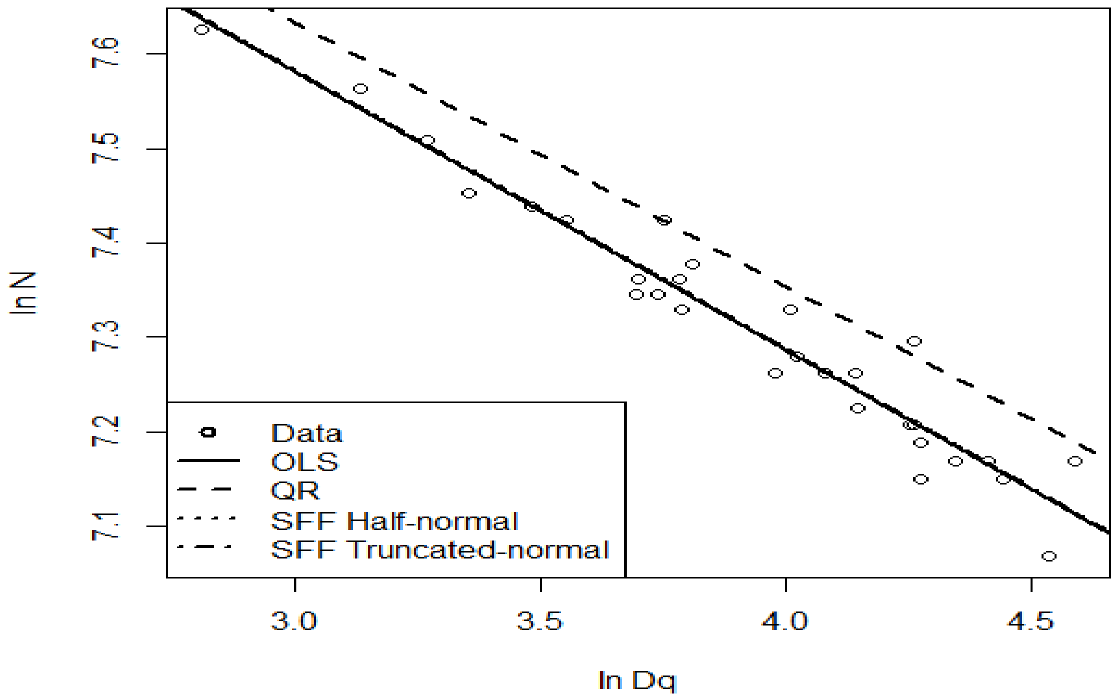
The timber cutting was defined as: removal (m^3 ha-1) ×Area (ha) of the stand.

RESULTS

Table 1: Values of the Parameter Estimators and Goodness- of- fit Statistics for the Reineke Model under OLS, SFR and QR

ESTIMATORS	β_0	β_1	R^2_{Adj}	$RMSE$	AIC	BIC	$\bar{X}\ E$	*Pr>[t]*
OLS	8.46398	-0.29414	0.93	0.03172497	-113.9032	-108.2980		<2e-16 <2e-16
QR	8.468015	-0.278555	0.66	0.07287954	-85.69624	-81.49265	__	<2.2e-16 <2.2e-16
SF HN	8.46398	-0.29414	0.94	0.03172473	-115.9032	-111.6996	0.9998771	<2.2e-16 <2.2e-16
SF TN	8.46445506	-0.29413686	0.93	0.03172843	-111.9032	-104.8972	0.9995171	<2.2e-16 <2.2e-16

OLS—Ordinary Least Squares, QR—Quantile Regression, SF HN Stochastic Frontier Half Normal and Stochastic Truncated Normal, β_0 – Intercept, β_1—Slope, R^2_{Adj} -- R Squares Adjusted, $RMSE$– Root Mean Square Error, AIC – Akaike Information Criteria, BIC --- Bayesian Information Criteria, $\bar{X}$ E -- Mean Efficiency.



OLS = Ordinary least squares; SF-TN= Stocastic Frontier Truncated normal; SF-HN=Stocastic Frontier Half normal, QR=Quantile Regression, 0= Data

Figure 2: Grand Model Assessment for Reineke's Model Parameters

Table 2: Stand Density Calculated with the Reineke Model Approach in its Half-Normal Form to Delimit the Competition Zones

		Tree Density by SDI Class			
S/N	**Dq**	**100%**	**55%**	**35%**	**20%**
1	15	2329	2131	2106	2096
2	20	2140	1958	1936	1926
3	25	2004	1834	1813	1803
4	30	1899	1738	1718	1709
5	35	1815	1661	1642	1633
6	40	1745	1597	1578	1570
7	45	1686	1543	1525	1517
8	50	1634	1496	1478	1471
9	55	1589	1454	1437	1430
10	60	1549	1418	1401	1394
11	65	1513	1385	1368	1361
12	70	1480	1355	1339	1332
13	75	1450	1327	1312	1305
14	80	1423	1302	1287	1281
15	85	1398	1279	1264	1258
16	90	1375	1258	1243	1237
17	95	1353	1238	1224	1218
18	100	1333	1220	1205	1199

Dq= Quadratic mean diameter (cm); SDI=Stand density index

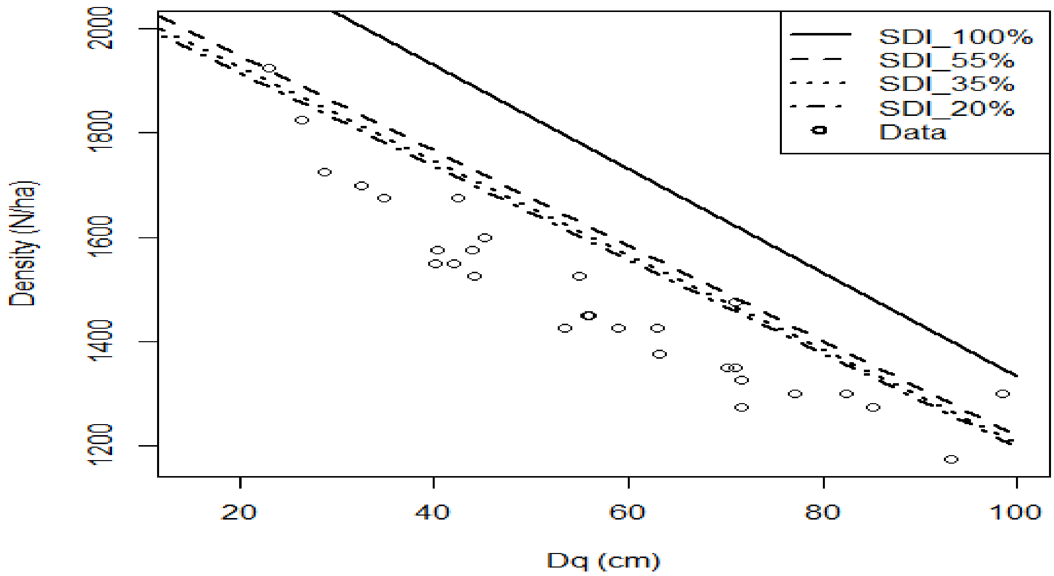


Figure 3: Stand Density Index diagram for even-aged stands of *Tectona grandis*

Table 3: Height Diameter Model Selection Indices of *Tectona grandis*

MODELS	INTERCEPT	SLOPE	AIC	BIC
1	45.8401	0.00836	5034.508	5050.136
2	44.8266	27.5064	5067.881	5083.509
3	16.03848	1.02647	9655.929	9672.419

AIC – Akaike Information Criteria, BIC --- Bayesian Information Criteria

Table 4: Volume Model Selection Indices of *Tectona grandis*

MODELS	INTERCEPT	SLOPE	AIC	BIC
1	-0.001475	0.9225	39648.53	39665.02
2	0.008.557	0.2107	41131.81	41148.3
3	0.0072	0.000085	39412.87	39429.36

AIC–Akaike Information Criteria, BIC---Bayesian Information Criteria

Table 5: Calculation of the Possibility in a Stand of 4 ha, Based on the Density Management Diagram of Reineke

N	Dq(cm)	THT	RS	SDI	VOL(IND)	VOL/HA	IC%	S/REGIME	REMOVAL	TIMB/CUT
1800	15	5.402532	1.924501	2594.671	0.110523	1105.234				
1800	50	15.66071	1.924501	1820.886	3.335101	33351.01	5.6	ACL	333.5101	1334.04
1700	50	15.66071	1.980295	1719.725	3.335101	33351.01	----	----	----	----
1700	60	18.08112	1.980295	1629.929	5.540024	55400.24	5.9	2ACL	554.0024	2216.01
1600	60	18.08112	2.041241	1534.051	5.540024	55400.24	----	----	----	----
1600	80	22.35516	2.041241	1409.582	12.16841	121684.1	12.5	3ACL	2433.682	9734.728
1400	80	22.35516	2.182179	1233.384	12.16841	121684.1	----	----	----	----
1400	100	25.97113	2.182179	1155.03	22.08266	220826.6	100	MT	30915.72	123662.9
0	0	0	0	0	0	0	----	----	----	----

NA= Number of trees ha^{-1}; Dq = Quadratic mean diameter; THT= Total individual height; RS= Relative spacing; SDI= Reineke's stand density index; VOL= Total stem volume with bark; IC= Cutting intensity; T = Silvicultural regime; ACL= Thinning; MT= Clear cutting,REM=Timber removed, Timber Cut.

DISCUSSION

Modeling is a vital tool for quantifying and managing forest growths. Therefore, Height-Diameter modeling of the *Tectona grandis* plantation is essential for predicting tree heights of the plantation. In the study, three (3) height-diameter models were developed and applied to predict the heights of trees in the plantation. Based on the model selection indices considered in table one (1), the result showed that model one (1) had the lowest selection indices of AIC (5034.508) and BIC (5050.136) when compared to model two (2) with AIC(5067.881), BIC(5083.509) and model three (3) with AIC(9655.929), BIC(9672.419). It is based on this premise that model one (1) is selected to be the best model and appropriate for predicting tree heights in the plantation. It is abysmal to engage in measuring total height of all trees in a given plantation in the course of carrying out a project due to the difficulties in visibility and fatigue posed by canopy cover. It is also crucial to be at breast with the current growing conditions of the plantation, particularly the total heights and diameter at breast heights in order to either sustain or adjust the management practices given to trees in the plantation

In table four (4) above, the result showed model selection indices for predicting tree volume. Model three (3) with AIC (39412.87), BIC (39429.36) has the lowest model selection indices when compare to model one (1) with AIC (39648.53), BIC (39665.02) and model two (2) with AIC (41131.81) and BIC (41148.3). Therefore, model three (3) was the grand and most suitable for predicting tree volume of the plantation.

In table one (1) above, The comparative assessment for selecting the best grand model among the different models used in estimating Reineke's model parameters and stand density index revealed that the stochastic frontier half normal (SF HN) was superior, as it exhibited the lowest RMSE (0.03172473), AIC (-115.9032), BIC (-111.6996) and $\bar{X}E$ (0.9998771). Therefore, model three (3) was also selected as the grand and most suitable for predicting tree densities of the plantation.

Stand Density Index

In table two (2) above, the stand density index was predicted at 20%, 35%, 55% and 100% to delimit the competition zones. The lower the stand density index, the fewer the number of trees and the greater it reaches upper limits of free growth zone. The estimation of the growth zones was derived from the methodology of (Camacho-Montoya *et al*., 2018).

Simulation of Thinning Regimes

The application of stand density index can be made based on the production objectives. Table five (5) exemplifies a regime of thinnings and final harvest in which a stand with 4 ha of forest area is described. The initial density is 1800 trees ha^{-1}($NA\ ha^{-1}$) with a quadratic mean diameter (Dq) of 15 cm in the first thinning (1ACL). It was decided to reduce the density to 1700 trees ha-1when the Dq = 50cm with a cutting intensity (IC%) of 5.6%. After this stage, the Dq continues to increase until reaching the lower limit of the self-thinning area, a second thinning (2ACL) was applied when a Dq = 60 cm was reached 1600 trees ha^{-1} with a cutting intensity (IC%) of 5.9% and a third thinning (3ACL) was applied when a Dq = 80 cm is reached 1400 trees ha^{-1} with a cutting intensity (IC%) of 12.5% and `1400 trees ha^{-1} were left standing to take full advantage of the area of constant growth. Subsequently, regeneration cutting treatment can be carried out with a clear cutting (MT) when the Dq reaches 100 cm.

According to the model and stand density index, it is not feasible to perform thinnings below 15 cm of quadratic mean diameter, because the development of stand has not reached a point of visible competition, and since it is sought to obtain economic benefits from the thinnings products when they are practiced at an early age, the wood extracted is of little commercial value. Santiago *et al.* (2017) mentioned that the use of growth models is required to generate the most important information for management decision making in time and space. Growth models aid in determining the natural mortality over time, and the age at which a certain value of Dq is accomplished.

CONCLUSION

The results showed that model one (1) of the H-D, model three of the volume and the stochastic frontier half normal (SF HN) model had the lowest selection indices, therefore, were selected as the grand and suitable models for proper management of the plantation. The stochastic frontier half normal (SF HN) model was apt to raise Reineke's model parameters and applied to predict the stand density index. The stand density index allowed the simulation of thinning regime for the stand and found the best management strategies to optimize the growing space and the redistribution of the growth of the remaining trees. These tools are keys for decision making when proposing cutting intensities in thinnings that prepare the plantation for the final harvest. The thinning regime should be specific for each stand, depending on its quadratic mean diameter and the number of trees per hectare, as well as the type of products to which the trees are to be removed.

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