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MODELLING STEM HEIGHT AND CROWN-WIDTH of *Tectona grandis* IN ILORIN, NORTHERN-CENTRAL NIGERIA

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ABSTRACT

This study modelled tree growth characteristics and also provided a thinning schedule that could be adopted in order to ensure sustainable management of the plantation. Single and Generalized Height-Diameter (H-DBH) models were adopted in predicting the height of tree stands. Ordinary least square (OLS) and Quantile regression (QR) were adopted in modelling crown width – diameter at breast height (CW-DBH) relationship. Models were assessed based on Akaike Information Criteria (AIC), Bayesian Information Criteria (BIC), Root Mean Square Error (RMSE), Relative Mean Absolute Bias (RMA) and Mean Absolute Percentage Error (MAPE). The Schroder and Alvarez (SAII) H-DBH model had the smallest AIC (4404), BIC (4435.95), RMSE (1.25), RMA (9.45) and MAPE (9.83) and relative rank sum of 5(1st). The OLS method performed best in modelling CW-DBH relationship by recording the lowest AIC (3564.3), BIC (3579.89), RMSE (0.92), RMA (22.28) value. The rotation age of the plantation was also estimated to be 21 years.

Keywords: Crown width, height, rotation age, thinning and teak.

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INTRODUCTION

Over the years, the application of forest growth models has become an intrinsic part of forestry research because they are generally used to predict future growth of forest stands. Beside prediction purpose, growth and yield models provide information that can aid and influence forest management practices and decisions. Effective management of the forest is possible only when reliable information on present and future forest conditions are available (Lee, 2018).

However, a major constraint in developing and applying growth models are the complexities involved in measuring some of these growth variables such as height and crown size. Shamaki*et al.*(2016) also opined that one of the greatest challenges in model development is measuring tree variables and data gathering. Most tree variables, which are difficult to measure directly such as crown size and height, are highly correlated with diameter which can be measured easily and accurately. As a result, most yield systems have relied on the use of height-diameter (H-DBH) and crown width-diameter at breast height (CW-DBH) models in estimating height and crown width of trees respectively. Forestry literature detailing the use and application of tree growth models such as H-DBH and CW-DBH models exist (e.g., Adesoye and Ezenwenyi, 2014, Briseno*et al.,* 2019; Ogana *et al.,* 2020) for natural forest and plantation.

Akindele in (2003) opined that sustainable forest management is anchored on obtaining information on the growing stock of the stand; and such information serves as a guide to the forest managers for evaluating and allocating forest area for exploitation. As a result, efforts have intensified to quantify the potential extent of present and future wood supply from the University of Ilorin plantation. Considerable effort has been applied by the management to collate data on the growth of the plantation; however, most of these data (crown size, height and diameter class) are incomplete and has made it difficult to quantify the current and future growth and yield of the plantation. Therefore, this study seeks to model Height-Diameter at breast height relationship, model Crown Width-Diameter at breast height relationship and then apply the models in providing a thinning schedule for the stand and also estimate the rotation age of the teak plantation. These will provide the institution and the manager of the plantation with necessary guides for rational decision making and management planning as well as its implementation. Models provided by this study will allow the manager/institution to link current growth with expected yield, thereby ensuring resource sustainability.

MATERIALS AND METHODS

Study area and data collection

The study was carried out on the University of Ilorin teak plantation, located in Ilorin-South of Kwara state Nigeria. The teak plantation is geographically located on latitude 8° 29' 30"and 8° 29' 0"N and longitude 04° 38' 30"and 04° 39' 0"E (Figure1). It is characterized by double rainfall maxima and has tropical wet and dry climate (Olanrewaju, 2009). It has an annual rainfall range of 1000 mm to 1500 mm and a temperature range of 25℃ to 30℃ during the wet season and 33 ℃ to 37 ℃ in dry season. The soils are predominantly derived from ferruginous and crystalline acidic rocks and are predominantly alfisols (Ajala*et al.*, 2020).

The plantation covers a total land area of 616 ha and it is comprising of five different age series. A stratified random sampling technique was adopted in laying out temporary sample plots (TSPs) across five age series (13, 12, 11, 10 and 9). The plantation was stratified based on their age series (5 strata). Sample plots of 25 m × 25 m were established randomly on the stands of each stratum. A total of 50 sample plots were established on the plantation with a sampling intensity of 0.51 %. The number of sample plots established on each stratum was determined by proportional allocation i.e., stands with larger areas had have higher number of sample plots (Table 1).

Total enumeration of all trees was carried out in each sample plot. Tree variables such as total height was measured with hypsometer, diameter at breast height was measured using a girth tape while diameter at different points along the stem (top, middle and bottom) was measured using a relaskop. Furthermore, crown width was measured as a linear distance between edges of the tree crown in North-South and East-West directions. The mean value of North-South and East-West measures was measured as crown width.

Table 1: Distribution of sample plots across age series

Age Series (years)	Area of Age Series (ha)	Number of Sample Plots
13	57	5
12	130	11
11	150	12
10	157	13
9	122	9
Total	616	50

Tree Height-Diameter Models

Several height-diameter models have been developed and applied to different forest stands including plantation. However, no single H-DBH model is suitable for all forest stands and as result, this study examined twenty (20) different H-DBH models and applied the best model to the stand. 10 single H-DBH models and 10 generalized H-DBH models were fitted to the data obtained from the stand.

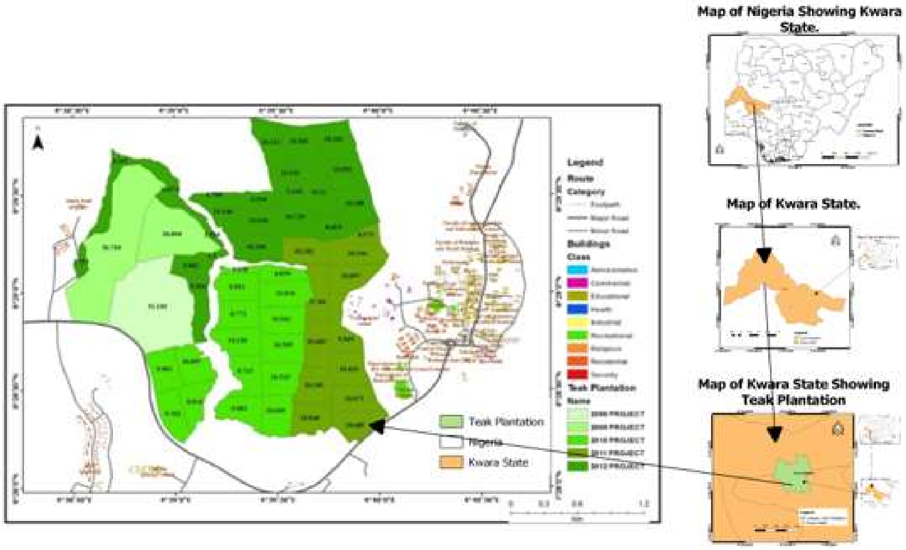

Figure 1: Map of Teak plantation located in University of Ilorin, Kwara state Nigeria

Table 2: Height-diameter models

Modelname	Equation	Reference	Eqn.
Naslund	$H = bh + \frac{DBH^2}{(a + bDBH)^2}$	Naslund (1937)	[1]
Gompertz	$H = bh + ae^{(-b\exp^{(-cDBH)})}$	Gompertz (1825)	[2]
Logistic	$H = bh + \frac{a}{(1 + bexp^{-cDBH})}$	Mehtataloet *al.* (2015), Ogana *et al.* (2020)	[3]
Meyer	$H = bh + a(1 - exp^{-bDBH})$	Meyer (1940)	[4]
Wykoff	$H = bh + exp^{a+b/(DBH+1)}$	Wykoff *et al.* (1982)	[5]
Ratkowsky	$H = bh + aexp^{-b/(DBH+c)}$	Ratkowsky (1990)	[6]
Richards	$H = bh + a(1 - exp^{-bDBH})^c$	Richards (1959)	[7]
Power	$H = bh + aDBH^b$	Stoffel and van Soest (1953)	[8]
Weibull	$H = bh + a(1 - exp^{bDBH^2})$	Yang and Huang (1978)	[9]
Prodan	$H = bh + \frac{DBH^2}{a + bD + cDBH^2}$	Strand (1959)	[10]
Sloboda	$H = bh + (H_d - 1.3)exp^{\left(a\left(1-\frac{DBH}{d_g}\right)\right)} exp^{b\left(\frac{DBH}{d_g}-\frac{1}{DBH}\right)}$	Sloboda *et al.* (1993)	[11]
Piennaar	$H = aH_d\left(1 - e^{\frac{-bDBH}{d_g}}\right)^c$	Pienaar *et al.* (1991)	[12]
SA I	$H = bh + (a + bH_d - cd_g)exp^{\frac{-d}{\sqrt{DBH}}}$	Schroder and Álvarez-González (2001)	[13]
Gen MM	$H = 1.3 + \frac{aDBH}{b + DBH}exp^{\frac{-c}{\sqrt{H_d}}}$	Oganaet *al.* (2020)	[14]
Tome	$H = H_d exp^{\left(a+bH_d+c\frac{N}{1000}+dAg\right)\left(\frac{1}{DBH}-\frac{1}{D_0}\right)}$	Tomé (1989)	[15]
Mrikovich	$H = bh + (a + bH_d - cd_g)exp^{\frac{-d}{DBH}}$	Mirkovich (1958)	[16]
Monnes	$H = bh + \left(a\left[\frac{1}{DBH} - \frac{1}{D_0}\right] + \left[\frac{1}{H_d - 1.3}\right]^{\frac{1}{3}}\right)^{-3}$	Mønness (1982)	[17]
Canadas	$H = bh + \left(a\left[\frac{1}{DBH} - \frac{1}{D_0}\right] + \left[\frac{1}{H_d - 1.3}\right]^{\frac{1}{2}}\right)^{-2}$	Cañadaset *al.* (1999)	[18]
SA II	$H = 1.3 + (a + bH_d - cd_g + dG)exp^{\frac{-e}{\sqrt{DBH}}}$	Schroder and Álvarez-González (2001)	[19]
Gaffrey	$H = 1.3 + (H_d - 1.3)exp^{a\left(1-\frac{d_g}{DBH}\right)+b\left(\frac{1}{d_g}-\frac{1}{DBH}\right)}$	Gaffrey (1988)	[20]

a, b, c, d, e: model parameters; bh: a constant used to account that DBH is measured at 1.3m above the ground; H: height (m); DBH: diameter; H_d: dominant height, D_o: dominant diameter, G: basal area/ha, d_g: quadratic mean diameter; N: trees per ha

Crown-width Diameter Relationship

Studies modelling crown width-diameter relationship have established a linear relationship between crown width and diameter for different species (Ogana 2019, Adesoye and Ezenwenyi 2014; and Lockhart *et al.* 2005). Therefore, this study considered a linear relationship which was adapted in Ogana (2019) and it is expressed as:

$$CD_{ki} = b_0 + b_1 DBH_{ki} + \varepsilon_{ki} \ldots\ldots [21]$$

Where CD is crown diameter (cm), DBH is diameter at breast height (cm), ε is the error term which is assumed to be normal and independent with a zero mean and a constant variance and b_0, b_1 are intercept and slope, the subscript $i$and k = individual tree $i$of plot k.

Two fitting methods were considered for fitting the equation [21] i.e. ordinary least square and quantile regression method.

Ordinary Least Square

This method estimates the conditional mean of the response variable i.e., crown diameter given a fixed value of another variable. The OLS will estimate the parameters in Eq. [21] by minimizing the sum of squared residuals of the function (Hao and Naiman 2007). It is however, most reliable only if the assumptions of normality, homoscedasticity and independence are met (Raptis*et al.,* 2018).

Quantile Regression

Similar equation form Eq. [21] was applied to estimate the τth crown diameter

$$\hat{y}_\tau (CD) = b_0 + b_1 DBH \ldots. [22]$$

Where $\hat{y}_\tau$ is the estimated value of the τth quantile of crown diameter at diameter of breast height (DBH), the parameters from the quantile regression were obtained by minimizing the sum of absolute residual expressed as:

$$\beta_\tau = argmin\beta\varepsilon R^2 \sum_{i=0}^{n} \rho_\tau (y_i - x_i^{!}\beta) \ldots..[23]$$

Where: β = parameter and τ = quantiles. Different quantiles were used including 0.5, 0.25, 0.75 and 0.95 were considered.

Application of models for the management of the stand

The best-performing function was applied to estimate stand variables. For the purpose of this study, the application of CW-DBH relationship was used in determining sustainable thinning regime/schedules for the management of the teak plantation. Hemery*et al.* (2005) opined that such thinning schedules are usually built on average diameter (DBH) of the stand to be realized. Several methods have been developed and applied however; the method used by Ogana (2019) was adopted for this study because of its simplicity. The method involves estimating the parameters from the CW-DBH model which is then used in prescribing thinning regimes for the stand. Variables such as crown width (CW), CW-DBH ratio (R), crown area (CPA), number of trees per ha (10000/CPA) and stand basal area $\{100000 * (\frac{\frac{\pi}{4}}{R^2})\}$ were estimated and thinning regimes were considered.

Model Application in Estimating Rotation Age of the Teak Plantation

In order to estimate the rotation age of the plantation, the yield, PAI and MAI were computed. The Schumacher's yield model was adopted in estimating the yield from ages 3 to 45 years. The adopted model is given as:

$$V = a \times exp^{\left(\frac{b}{A}\right)} \ldots..[24]$$

Where V = volume, A = Age

Evaluation and Assessment of models

Models were compared by Root Mean Square Error, Coefficient of Determination, Akaike Information Criteria and Bayesian Information Criteria. For all models, plots of residuals vs. predicted values were used as graphic inspection analysis to check for possible heteroscedasticity trends.

RESULTS

A total of 1137 sample trees were measured from all the age series: 13, 12, 10, 9, and 8 years respectively. The summary statistics of the data obtained from the 5-age series are presented in table 3. The mean values of individual tree growth characteristics for year 13 (Height, DBH, and CW) are 9.71±1.28 m, 13.94 ±2.66 cm, 2.77±0.78 m, respectively.

Furthermore, the mean values of individual tree growth variables (H, DBH and CW) for year 12 are 10.84±1.63 m, 14.55±2.77 cm and 2.77±0.78 m, respectively. The year 11 recorded mean values of 9.62 ±1.58 m, 13.23 ±2.82 cmand 3.48±0.80 m for height, diameter and crown width respectively. The summary statistics for 10-year teak stand shows the mean values for height, diameter at breast height and crown width to be 11.39±2.34 m, 14.29 ±3.67 cm and 3.61 ±1.06 m, respectively. The 9-year old teak stand recorded mean values of 7.07 ±2.06 m, 11.89 ±1.28 cm and 2.81±0.42 m for height, DBH and crown width respectively.

A summary of stand variables as also presented in table 3 shows that numbers of trees per hectare ranged between 80 and 880 trees/ha across the age series. Lower number of trees/ha were recorded for the 9-year-old teak stand while greater number of trees/ha were recorded for the 13-year-old teak stand. Furthermore, basal area/ha ranged between 1.0and 16.71m^2/ha. The 9-year-old teak stand recorded the lowest basal area/ha while the 10year old teak stand recorded the highest basal area/ha. Dominant height recorded across the age series ranged between 5.80 and 16.60m. The 10-year-old stand recorded the highest dominant height while the 9-year-old recorded the lowest value.

Table 3: Descriptive statistics of the measured and derived variables

Age	Statistics	Variables						
		H (m)	DBH (cm)	CW (m)	N (trees/ha)	G (m^2/ha)	Dq (cm)	H_d (m)
13	Mean	9.71	13.94	2.77	615.63	9.7	14.18	11.53
	SD	1.28	2.66	0.78	189.45	2.94	0.61	0.85
	Min	6.7	10	1.12	400	6.08	13.50	10.3
	Max	13.1	22	6.29	880	13.74	15.40	12.6
12	Mean	10.84	14.55	2.55	672.68	11.56	14.78	12.87
	SD	1.63	2.77	0.85	120.06	2.38	0.86	1
	Min	6.3	10	0.60	304	5.98	13.50	11.6
	Max	21.5	22.8	5.86	800	14.42	16.70	14.6
11	Mean	9.62	13.23	3.48	464.52	6.87	13.50	11.4
	SD	1.58	2.82	0.8	150.87	2.76	0.90	1.11
	Min	3.6	10	1.3	160	1.76	11.70	9.4
	Max	15.3	26.5	7.25	688	11.29	14.90	13.4
10	Mean	11.39	14.29	3.61	511.73	8.93	14.61	13.42
	SD	2.34	3.67	1.06	146.16	3.89	1.45	2.34
	Min	5.4	10	1.66	80	1.12	12.70	7.7
	Max	18.2	27.5	10.94	720	16.71	17.20	16.6
9	Mean	7.07	11.89	2.81	128.74	1.4	11.94	7.51
	SD	2.06	1.28	0.42	45.03	0.4	0.80	1.42
	Min	3.4	10	1.58	80	1	10.70	5.8
	Max	13	15	4.18	208	2.14	13.70	9.6

H = total Height, DBH = Diameter at Breast Height, CW = Crown Width, N = Number of Trees/ha, Basal Area/ha, D_q = Quadratic mean, H_d = Dominant Height

Parameter estimates of fitted individual and generalized H-DBH models

The models for predicting tree height in University of Ilorin teak plantation have been fitted and evaluated. Their results are presented in Table 4. In fitting the data set, the result showed that the RMSE, AIC, BIC, MAPE and RMA of the single H-DBH models ranged from 1.76 – 1.77 m, 5309.11 – 5324.20, 5324.70 -5339.80, 14.04 – 14.11, 13.08 – 13.19 while that of the generalized ranged from 1.25 – 18.40 m, 4404.77 – 11576.45, 4435.95 – 11586.85, 9.83 – 167.88 and 9.45 – 387.44 respectively. Parameters of the single H-DBHmodels were significant in the models however, when the models were assessed based on the goodness of fit (GOF) indices, the single H-DBH models performed poorly in predicting the height of teak in the study area when compared with the generalized models. The goodness of fit indices recorded higher values for the single H-DBH models than the generalized.

The assessment of the models based on their ranks with respect to the goodness of fit indices showed that SAI II performed best in estimating the height of teak in the study area with a rank sum of 5 (1^{st}) just ahead of Mirkovich (5.01) (2^{nd}), SAI (5.01) (2^{nd}), Pienaar (5.09) (3^{rd}) and Gen MM (5.09) (3^{rd}). Gaffery and Canadas had the highest rank sum of 9.46 and 18.88, respectively (Table 5). The single H-DBH models provided identical ranks with respect to the goodness of fit indices.

It important to state that the regression line was fitted based on some certain assumption about the error term. Some of the assumptions include; the error term must be independent, have a zero mean, constant variance and should be normally distributed. However, these assumptions should not be blindly accepted hence the need to carry out a residual analysis of each model. The residual contains all available information on the way in which the model fails to properly explain the observed variation in the dependent variable.

The results of visual test carried out on the residual of SAI II model is presented in figure 2 represents plot showing equal variance and the result indicates that the residual satisfied the assumption of homoscedasticity since it has its horizontal band spread from -5 to +5. The result also shows that the residuals were independent of each other and it also had its mean to be zero. Fig2 shows that the assumption of normality was also satisfied by the SAI II model. Therefore, the SAI II model can be adopted in estimating tree height in the study area without much error.

Table 4: Parameter estimate of fitted H-DBH models

Model Name	**Parameter Estimates**				
	a	**b**	**c**	**d**	**e**
Naslund	1.419*	0.228*			
Gompertz	12.788*	2.340*	0.141*		
Logistic	12.401*	4.413*	0.182*		
Meyer	15.361*	0.065*			
Wykoff	2.886*	-9.94*			
Ratkowsky	16.76*	7.96*			
Richards	13.15*	0.11*	0.11*	1.56*	
Power	1.93*	0.58			
Weibull	11.08*	-0.01*			
Prodan	4.69*	0.27	0.06*		
Sloboda	11.90*	0.18*			
Pienaar	1.08*	1.27*	0.70*		
SAI	5.38*	1.65*	0.36*	3.01*	
Gen MM	85.74*	9.00*	-6.07*		
Tome	2.71*	0.01	0.002	0.04	
Mirkovich	3.60*	1.11*	0.23*	5.73*	
Monnes	-7.75*				
Canadas	7.01*				
SAI II	3.27*	1.78*	0.25*	-0.12*	3.02*
Gaffery	0.02	6.84			

**Signifies that the parameters are significant. a, b, c, d and e are regression parameters*

Table 5: Goodness of fit indices for single and Generalized H-DBH models

Model Name	RMA	RMSE	MAPE	AIC	BIC	$\sum Sum$
Meyer	13.08	1.76	14.06	5310.98	5326.57	7.77
Naslund	13.08	1.76	14.05	5309.92	5325.52	7.77
Gompertz	13.09	1.76	14.04	5311.04	5331.83	7.78
Logistic	13.09	1.76	14.04	5311.39	5332.18	7.78
Wykoff	13.08	1.76	14.04	5309.11	5324.70	7.76
Ratkowsky	13.08	1.76	14.04	5310.75	5331.54	7.78
Richards	13.08	1.76	14.04	5310.91	5331.70	7.78
Power	13.11	1.77	14.11	5318.65	5334.24	7.79
Weibull	13.19	1.77	14.08	5324.20	5339.80	7.8
Prodan	13.08	1.76	14.04	5310.71	5331.50	7.78
Sloboda	13.12	1.76	14.05	5312.93	5328.53	7.77
Pienaar	9.75	1.27	9.98	4436.12	4456.91	5.09
SAI	9.5	1.26	9.87	4412.04	4438.03	5.01
GenMM	9.68	1.27	9.99	4438.06	4458.85	5.09
Gaffery	14.66	2.12	18.43	5808.35	5823.94	9.46
Tome	-	6.84	53.50	8936.01	8962	-
Mirkovich	9.51	1.26	9.87	4410.14	4436.13	5.01
Monnes	387.44	18.4	167.88	11576.45	11586.85	41
Canadas	92.31	5.42	43.18	8310.34	8320.74	18.88
SAII	9.45	1.25	9.83	4404.77	4435.95	5

RMA = Relative mean absolute bias, RMSE = Root Mean Square Error, MAPE = Mean Absolute Percentage Error, AIC = Akaike Information Criterion, BIC = Bayesian Information criterion

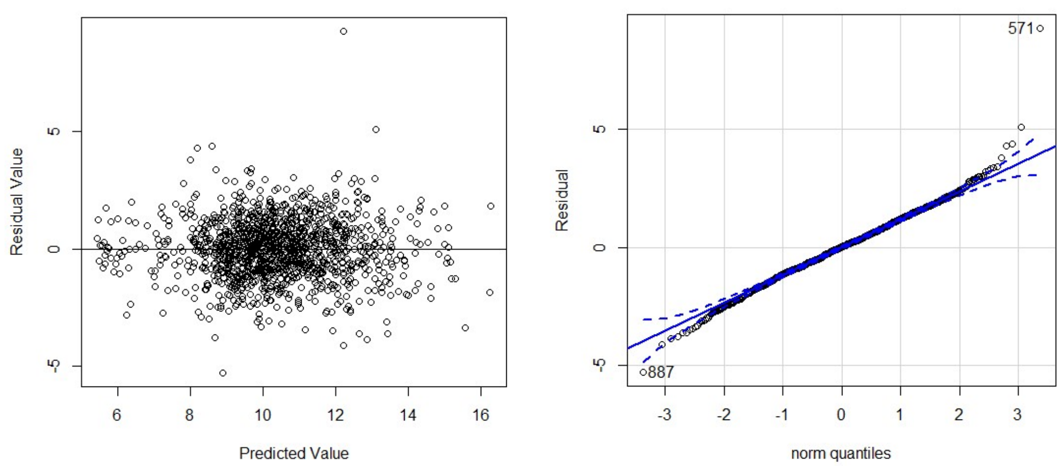

Figure 2: Residual plots of fitted H-DBH models

Modelling crown width-diameter relationship

The estimated parameters and fit indices from ordinary least squared (OLS) and quantile regression for modelling the relationship between crown width (CW) and DBH of *T. grandis* are presented in Table 6. The different quantiles adopted for the study were 0.5, 0.25, 0.75 and 0.95 quantiles. The result shows that all methods adopted in modelling the CW-DBH relationship recorded positive intercepts which lied between the range of 1.25 and 1.74. The parameter estimates for the OLS method were significant while the parameters of the quantile regression method were not significant. The OLS method recorded R^2, RMSE, AIC, BIC and RMA value of 0.20, 0.92 m, 3564.30, 3579.89 and 22.28 respectively while the quantile method recorded a R^2, RMSE, AIC, BIC and RMA range of -1.70 -0.19, 0.91 – 1.63 m, 3565.44 – 5115.62, 3581.04 - 5131.22 and 22.14 – 33.52 respectively. Based on the fitting statistics (Table 6), the OLS fitting method performed slightly better than the quantile method and, therefore, it was selected as the basis for modelling CW-DBH relationship in the study area. It is also important to state that all methods adopted for the study recorded very low R^2 values.

To illustrate the differences in CW-DBH ratios at different diameter points, the best regression equations suggested in Table 6 was used to calculate CW-DBH values in Table 7. CW-DBH ratios variation along different diameter range was apparent, particularly at smaller stem diameters (<20 cm DBH). High initial values for CW-DBH ratio were first recorded but the ratio reduced as stem diameter increased. The result also showed that when stem diameters was between the ranges of 30-40 the ratio began to stabilize with the decline becoming less rapid.

Table 6: Estimated parameters from ordinary least square (OLS), quantile regressions (QR) and their fit indices

Methods	Parameters			Fit Indices			
	a	**b**	**Adj R**	**RMSE**	**AIC**	**BIC**	**RMA**
OLS	1.25	0.13	0.5	0.92	3564.3	3579.89	22.28
5%	1.37	0.12	0.15	0.91	3565.44	3581.04	22.14
25%	1.11	0.1	0.19	1.08	4021.12	4036.72	33.52
75%	1.21	0.17	0.18	1.08	4008.02	4023.61	22.7
95%	1.74	0.19	-1.7	1.63	5115.62	5131.22	31.77

Adj R = Adjusted Coefficient of determination, RMSE = Root Mean Square Error, AIC = Akaike Information Criterion, BIC = Bayesian Information Criterion, RMA = Relative Mean Absolute Bias.

Stand characteristics and thinning schedules for the teak plantation

The estimated parameters from ordinary least square (OLS) were further applied to prescribe thinning regime for the *T. grandis* plantation at the University of Ilorin. Table 7 shows the estimated crown width (CW), CW-DBH ratio (R), crown area (CPA), number of trees per ha, stand basal area, and the average spacing required (Sp). These estimates were obtained from the CW-DBH relationship modelled using the OLS method. From the table, different thinning regimes were considered for the study (i.e. light, medium, and heavy thinning) and the prescribed regime was developed based on mean stem diameter to be retained on the stand.

For example, if an average DBH of 20.58 *cm* was considered, the average crown diameter would be 9.7 *m*, and the crown would occupy an area of 94.09m^2, indicating that if competition between crowns is to be avoided at the time the stems reach 20.58 cm DBH, there should be no more than 10,000/ 94.09 = 106 stems/ha. Similarly, if the trees are then thinned to a final crop spacing and clear-felled when average DBH is 30.0 *cm,* if light thinning is to be considered a total of 12 trees will be removed to maintain a basal area of 30m^2in the stand. Furthermore, if medium or heavy thinning is desired, a total of 19 or 26 trees will be removed in other to maintain an average basal area of 25 or 20m^2/ha respectively in the stand.

Model Application in Estimating Rotation Age of the Teak Plantation

In simulating what the rotation age of the plantation is expected to be at maturity, the Schumacher's yield function was adopted in estimating the volume of material that can be obtained given the age of the stand. The parameters of the function were further applied in estimating future yield that could be obtained at different years from the plantation. From figure 4, the yield, PI, PAI and MAI were estimated for different years ranging from 3 to 45 years. The plot between PAI and MAI (fig 3) shows that the expected rotation age for the stand is 21 years. Also, to be noted is that the MAI plot shows no form of increment beyond the point of rotation.

Table 7: Stand characteristics and thinning schedules for the teak plantation

DBH (m)	CW (m)	R	G (m^2/ha)	N (trees/ha)	CPA	SP (m)	D_q (cm)	Volume (m^2)	Thinning Regimes Heavy 20	Medium 25	Light 30
0.1	2.55	25.5	12.08	1537	6.5	2.6	3.16	87.87	0	0	0
0.15	3.2	21.33	17.26	976	10.24	3.2	4.75	155.07	0	0	0
0.2	3.85	19.25	21.19	674	14.82	3.9	6.33	217.36	38	0	0
0.25	4.5	18	24.24	493	20.25	4.5	7.91	273.16	86	0	0
0.3	5.15	17.17	26.65	377	26.52	5.2	9.49	322.47	94	23	0
0.35	5.8	16.57	28.6	297	33.64	5.8	11.07	366.34	89	37	0
0.4	6.45	16.13	30.21	240	41.6	6.5	12.66	405.6	81	41	2
0.45	7.1	15.78	31.55	198	50.41	7.1	14.24	440.74	72	41	10
0.5	7.75	15.5	32.69	166	60.06	7.8	15.83	472.64	64	39	14
0.55	8.4	15.27	33.67	141	70.56	8.4	17.44	501.78	57	36	15
0.6	9.05	15.08	34.52	122	81.9	9.1	18.98	528.15	51	34	16
0.65	9.7	14.92	35.27	106	94.09	9.7	20.58	552.88	46	31	16
0.7	10.35	14.79	35.93	93	107.12	10.4	22.18	575.7	41	28	15
0.75	11	14.67	36.51	82	121	11	23.81	596.95	37	26	15
0.8	11.65	14.56	37.04	73	135.72	11.7	25.42	616.94	34	24	14
0.85	12.3	14.47	37.51	66	151.29	12.3	26.9	634.91	31	22	13
0.9	12.95	14.39	37.93	59	167.7	13	28.61	652.76	28	20	12
0.95	13.6	4.32	38.32	54	184.96	13.6	30.06	668.6	26	19	12
1	14.25	14.25	38.68	49	203.06	14.3	31.7	684.56	24	17	11

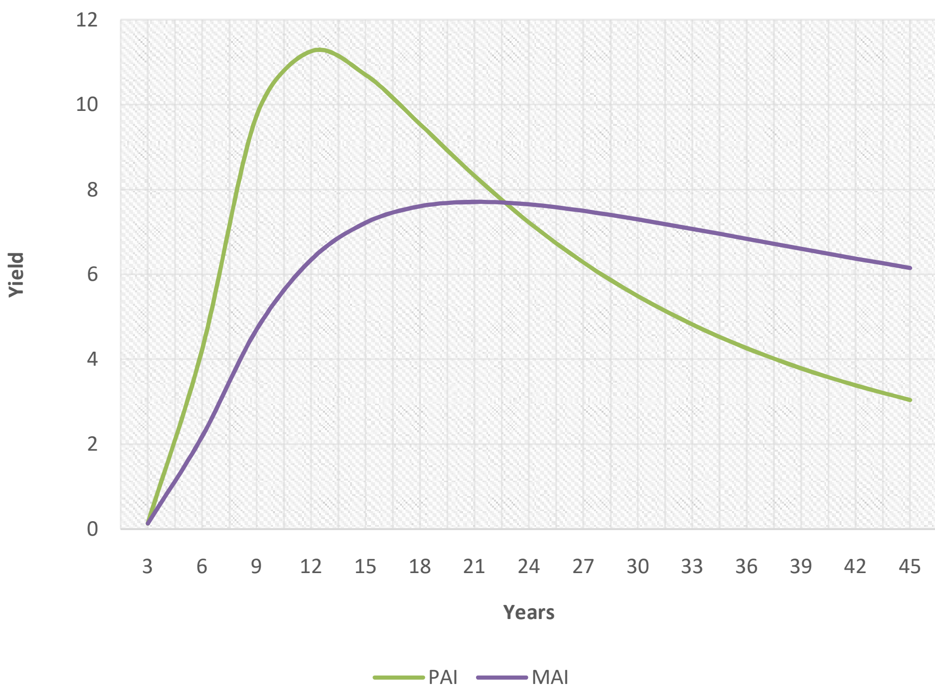

Figure 3: Graph of MAI against PAI

DISCUSSION

Fitted Individual and Generalized H-D Models

Several studies have made efforts in establishing models that could best estimate tree height of different tree species. Methods adopted by these authors have varied across different study areas. Brisenoet al.(2020) compared ten generalized H-DBH models for seven pine species in Durango, Mexico. It was concluded that modelling H-DBH relationship with just a single predictor variable i.e. diameter, may not be adaptable to different stand dynamics and silvicultural conditions; and as such, may not possibly estimate all H-DBH relationships in the stands. This statement agrees with this study as it was observed that the single H-DBH models which had diameter as the single predictor variable performed poorly in estimating tree height in the study area. However, when stand variability was incorporated into the models it improved the prediction of height in the study area. In this study, the Schroder and Alvarez (S.A II) model performed best in estimating tree height in the study area and this agrees with the results obtained by Ogana *et al.* (2020) who reported a good performance of the Schroder and Alvarez (S.A II) model when they examined the performance of some nonlinear mixed-effect height-diameter model for

Pinus pinaster* and *Pinus radiate.

Models for estimating the height of teak stands in Nigeria have been developed by a number of authors. Shamaki*et al.* (2016) developed models for estimating the height of teak in Nimbia forest reserve. The Chapman Richards and Weibull functions were adopted for the study;however, it was reported that the Chapman Richards function was more suitable in estimating the height of teak in the study area. The result of this study is in contrast to what was reported by Shamaki*et al.* (2016) as this study observed that the Chapman Richards function performed poorly in estimating the height of teak in the study area. This variation in performance can be attributed difference in location and data structure.

Studies have shown that the generalized form of H-DBH models provides a more accurate and reliable estimate of height than the single H-DBH models. Therefore, the generalized H-DBH model developed in this study would be valuable to the plantation manager and institution as it would provide reliable and accurate estimate of height more so, only few sample treesare needed to obtain information of the height of trees in the teak stands.

Modeling Crown Width-Diameter Relationship

The results obtained from modeling CW-DBH relationship using the ordinary least square and quantile regression method shows that both methods produced a positive intercept. The implication of this as opined by Foli*et al*. (2003) is that "the stand basal area could be allowed to increase towards maturity because CW-DBH ratio decreases with stem size". The result of this study agrees with the study carried out by Ogana (2020) who also observed a positive intercept in modeling CW-DBH relationship of teak in Omo forest reserve. The result of this study produced very low coefficients of determination and this favors the suggestion made by (Rouvinen and Kuuluvainen 1997, Bragg 2001) that crown width models that are developed using DBH as the only predictor may be sufficiently accurate for stands where the densities are similar, but not for stands with a wide range of stand conditions. It was observed that the stand conditions of the teak plantation varied widely moving from one age series to another and this may have been responsible for the low coefficient of determination value. Teak is a strong light demanding species that responds well to thinning. However, it was observed that some of the stands were not evenly spaced while some stands were overstocked. The implication of these is that delayed thinning results in stagnation and loss of growth potential while wide spacing and exceptionally heavy thinning may result in epicormic shoots and side branching as reported by Phillips (1995). Well documented reports on thinning regimes are still lacking but a great deal of silvicultural experience in Southern Asia, East and West Africa and Central America supports these assertions (Phillips, 1995).

One important application of modelling CW-DBH relationship is its application in prescribing thinning regimes for the management of the stand (Ogana, 2020). This thinning regime is usually built based on average diameter to be realized from the stand (Hemery *et al.,* 2005). Prescription of a thinning program for teak plantation in Nigeria has been the subject of similar investigations .e.g. Ogana in (2020) applied the CW-DBHrelationship in prescribing thinning regimes for teak stand in Omo forest reserve. These studies are geared towards helping the sustainable management of the *T. grandis* plantation forest in Nigeria.

Estimating the Rotation Age of the Plantation

Rotation age is also known as Production period. It is the period which a forest crop takes between its formation and final felling. It expresses the rate of growth of the crop to produce the desired size and quality of crop. The rotation length for the teak plantation at the University of Ilorin has not yet been defined. In this study, the biological rotation age was estimated to be 21 years. Rotation differs from species to species. Also, to note is that rotation differs for same species from region to region. Rotation is not a permanent one for a species at a particular site and can be increased or decreased. On this note, some studies have reported different rotation ages for teak such as Canadas *et al.* (2018) who reported a rotation age of 15 years for the most productive sites and 26 years for the least productive sites, for teak grown as living fences The difference in rotation age could be attributed to prevailing conditions such as climate and site quality. Kollert and Cherubini (2012) in their report of Forest Resource Assessment reported a minimum and maximum MAI of teak for Africa to be 3 and 21 m^2/ha/year respectively. A rotation period of 4 and 60 years was also reported as the minimum and maximum rotation respectively. The result of this study shows that the MAI and rotation age of the teak plantation falls within the minimum and maximum values reported by the authors.

Kollert and Cherubini, (2012) also suggested that for most plantations, "Rotation periods are rather short and span in most cases 20 to 30 years. This only allows for the production of small dimension logs, which are not in demand on the international market. Yet, this lesser-quality teak is suitable as a multi-purpose timber for less-demanding building purposes, furniture, flooring, reconstituted wood products, wood fuel and utility poles for transmission lines. Good quality logs for high-end uses, which have special technical and aesthetic properties, can only be produced in longer rotations". This suggestion agrees with the management objective of the teak plantation at the University of Ilorin as the sole aim of the plantation is for pole production and therefore the management decisions have been directed towards achieving this objective.

CONCLUSION

This study has modelled the growth and yield of plantation grown teak at the University of Ilorin. The study fitted 20 H-DBH model which includes single and Generalized H-DBH models. The result of the study shows that SAI II model will provide accurate estimate of the height of teak in the study area. This study also assessed the relationship between tree crown diameter and diameter at breast height (CW-DBH) using different modelling methods. The result of the study shows that the OLS method was more effective in modelling the CW-DBH relationship of teak in the study area. The CW-DBH relationship was used to derive different thinning schedules based on average diameter. The limiting stocking per ha, basal area per ha and growing space were defined. Furthermore, the rotation age of the teak plantation was also determined by plotting the MAI and PAI of the teak plantation. This information would help in the sustainable management of the *T. grandis* plantation in the University of Ilorin.

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