Annals of Silvicultural Research
43 (2), 2019: 89-96
https://journals-crea.4science.it/index.php/asr

Technical Note

Modelling Crown-Stem Diameters Relationship for the Management of *Tectona grandis* Linn f. Plantation in Omo Forest Reserve, Western Nigeria

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Received 20/03/2019 - Accepted 17/07/2019 - Published online 30/11/2019

Abstract - Crown-stem diameter relationship is important for sustainable forest management. Effective forest management requires routine inventory data of tree crops for decision making. Therefore, in this study, crown-stem diameter relationship was modelled for the management of *Tectonia grandis* L. f. plantation in Nigeria. The dataset consists of 1,919 trees measured from 35 sample plots. Three methods including ordinary least square (OLS), quantile regression (QR) and linear mixed model (LMM) were used to model the relationship between crown diameter (CD) and diameter at breast height (DBH). The model was used to estimate the limiting density, growing space and projection area. The result shows that the model from LMM was more suitable than OLS and QR. It explained 0.622 of the variation in CD with root mean squared error of 0.736. The study also shows e.g., that *T. grandis* trees of 25 cm DBH would occupy an equivalent area 36.32 m^2 and to avoid inter-tree competition the stand density should not exceed 275 Nha^{-1}. And if the plantation is to be thinned and clear-felled when mean DBH is 50 cm, density remaining after thinning would be 115 Nha^{-1} with average growing space of 9.3 m. This information would help in the management of the plantation.

Keywords - crown diameter; linear mixed model; ordinary least square; quantile regression; teak.

Introduction

Crown is an important part of trees which is required for photosynthesis and reproduction. The leaves on the crown absorb sunlight in the form of radiant energy for photosynthesis (Sharma et al. 2016). Photosynthesis is essential for the survival of tree crops. The larger the tree crown, the more foliage for photosynthesis; in consequence, more potential for carbon fixation (Zarnoch et al. 2004, Yang and Huang 2017). The condition of the crown gives information on the health status of the tree, because the crown often shows the first sign of deterioration (Zarnoch et al. 2004). Tree crowns are also required for bird nest and perching (Deng et al. 2003). Crown characteristics such as crown length and crown width/diameter, are routinely measured for quantification and better understanding of tree production efficiency, stability and vigor (Fu et al. 2017). They are also important for the prediction of "growth responses in spacing, thinning and fertilizer trials" (van Laar and Akca 2007). Crown characteristics with other growth variables have been used for forest growth and yield prediction (Gonzalez-Benecke et al. 2014, Fu et al. 2016).

Crown diameter (CD) has been defined as the "average of the widest axis of the crown and its perpendicular axis" (Zarnoch et al. 2004). It is a determinant of crown surface area, volume, crown form index, crown thickness index, linear crown index and crown spread ratio (van Laar and Akca 2007). CD has also been used to estimate canopy cover (Gill et al. 2000) and for crown profile analysis (Marshall et al. 2003, Raptis et al. 2018). Crown diameters are difficult to measure on the field, especially in forest stand with irregular edges (Kershaw et al. 2017, Fu et al. 2017). Thus, CD is often obtained as photo-derived variable from remote sensing (Gering 1995, Kershaw et al. 2017). Also, forest managers have depended on the ability to predict crown diameter from diameter at breast height/stump diameter based on a simplified relationship (e.g., Bechtold 2003, Foli et al. 2003, Hemery et al. 2005, Sönmez 2009, Pretzsch et al. 2015). This relationship can be established either through the method of ordinary least squared (OLS), linear mixed model (LMM) or quantile regression (QR)

Classic OLS has been recognized as one of the best methods of estimating conditional mean of response variables for a given value of predictor vari-

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http://dx.doi.org/10.12899/asr-1865

Table 1 - Descriptive statistics of the fitting (75%) and validation data sets (25%).

Variables	Fitting data (n = 1439)				Validation data (n = 480)			
	Mean	Max	Min	SD	Mean	Max	Min	SD
DBH (cm)	17.9	38.8	6.0	5.47	17.8	37.8	7.9	5.10
Height (m)	16.7	25.6	7.1	3.49	16.7	26.5	6.6	3.55
CD (m)	5.7	10.9	2.9	1.19	5.7	10.5	2.2	1.19
CPA (m^2)	27.4	94.1	6.6	11.45	27.3	87.4	3.8	11.59
BA (m^2)	0.027	0.118	0.002	0.01	0.027	0.112	0.004	0.01

N = 1919 trees; CD = crown diameter; CPA = crown projection area; BA = basal area; SD = standard deviation

able (Zhang et al. 2005). In OLS, the estimates of the parameters of CD-DBH relationship are obtained by minimizing the sum of squared residuals (Hao and Naiman 2007). It is however, most reliable only if the assumption of normality, homoscedasticity and independence are met (Sun et al. 2017). The problem of independence is overcome in linear mixed model. Most inventory data used for modelling are hierarchical or nested in nature i.e., tree in plot; such data structure is effectively modelled using mixed-effect approach. This approach considered both within and between-plots variability. Thus, because of the fixed and random parameters in linear mixed model, the covariate effect and heterogeneity between plots are better explained (De-Miguel et al. 2012, Sun et al. 2017). The quantile regression (QR) is another approach that is gaining wide application in forestry. In QR, the problem of optimization is solved by minimizing the sum of absolute residuals (Zhang et al. 2005). It was introduced by Koenker and Bassett (1978). And since then, several researchers have applied this method to forest resources management because of its relative flexibility and robustness (e.g., Zhang et al. 2005, Gao et al. 2007, Mehtatalo et al. 2008, Ducey and Knapp 2010, Bohora and Cao 2014, Gao et al. 2016, Sun et al. 2017, Raptist et al. 2018, Ozcelik et al. 2018). QR provides detailed estimation to different parts of the dependent/response distribution without restriction on the assumption of the error term (Zhang et al. 2005, Sun et al. 2017).

Tectona grandis L. f. (teak) is a tropical hardwood species belonging to the family of Verbenaceae. It originated from the Asia-Pacific and can be found in some tropical countries including Brazil, Costa Rica, Kenya, Panama, Togo and Nigeria (Sousa et al. 2011). It was introduced in Nigeria to augment other slow-growing indigenous tree species and has been widely cultivated across length and breadth of the country. *T. grandis* is an important timber species that is fast-growing, it is of excellent anatomical and physical properties (e.g., it is durable, resistant to termite, easy of working, etc.) (Chukwu and Osho 2018). *T. grandis* can be used for different purpose because of its excellent properties and as such, there is high market demand for its products (Miranda et al. 2011). Thus, the need for its management. Effective forest management requires routine inventory data of the tree crops for decision making. The knowledge of crown diameter-DBH relationship can be used to determine tree spacing, stand density, basal area per ha, thinning regimes etc. (Hemery et al. 2005, Pretzsch et al. 2015). This information is relevant for sustainable forest management. Therefore, the main purpose of this study was to develop crown diameter-DBH relationship for the management of *T. grandis* plantation in Nigeria using different modelling methods.

Methodology

Data

The *Tectona grandis* L. f. data set from Omo Forest Reserve was used in this study. The plantation occupies an area of 139,100 ha and its lies between Latitudes 6°35′ to 7°03′N and Longitudes 4°09′ to 4°40′E of Ogun State, Nigeria (Chukwu and Osho 2018). The data set consists of 1919 trees measured from 35 sample plot of 25 x 25 m size. Diameter at breast height (DBH), total height and crown diameter (CD) were measured to the nearest 0.1 cm, 0.1 m and 0.3 m, respectively. CD was measured as the linear distance between edges of the tree crown in a north-south and east-west directions. The mean value of north-south and east-west measures was recorded as the crown diameter. The data set was randomly split into two groups – 75% (1.439) and 25% (480). The 75% was used for model fitting while the 25% was used for model validation. The descriptive statistics of the fitting and validation data sets are presented in Table 1.

Crown diameter (CD)-DBH relationship

Several studies have established linear relationship between tree crown diameter (CD) and diameter at breast height (DBH) for different species (Gering et al. 1995, Foli et al. 2003, Hemery et al. 2005, Adesoye and Ezenwenyi 2014, Yang and Huang 2017, Raptis et al. 2018). Furthermore, Dawkins

(1963) showed that the relationship between crown diameter and DBH can be effectively represented by straight lines. In this study, a scatterplot of crown diameter and DBH also showed a linear relationship with positive intercept (Fig. 1).

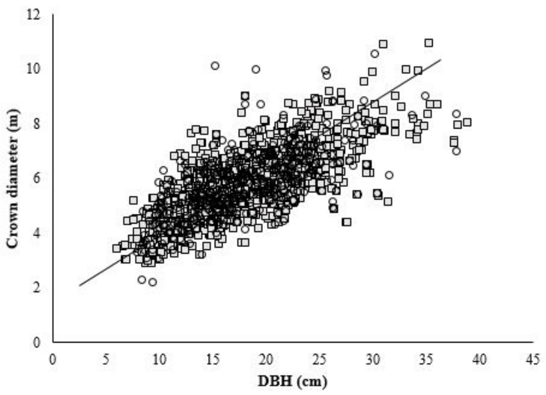

Figure 1 - Scatterplots of the relationship between crown diameter and DBH for the fitting data (squares) and validation data (circles).

Thus, a linear relationship was considered in this study. The model expression is given by:

$$CD_{\kappa i} = b_0 + b_1 DBH_{\kappa i} + \epsilon_{\kappa i} \quad (1)$$

Where CD = crown diameter (m), DBH = diameter at breast height (cm), and = intercept and slope, respectively, = error term which is assumed to be normal and independent with a zero mean and constant variance i.e., . The subscript i and k = individual tree i of plot k.

Fitting methods

Three fitting methods were considered in this study including ordinary least square (OLS), quantile regression (QR) and linear mixed model (LMM).

Ordinary Least Square (OLS)

This method estimates the conditional mean of the response variable i.e., crown diameter given a fixed value of another variable. The OLS estimated the parameters (and) in Eq.1 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 (Raptist et al. 2018).

Quantile Regression (QR)

Similar equation form (Eq. 1) was applied to estimate the **τ**th crown diameter quantile:

$$\hat{y}_\tau(CD) = b_0 + b_1 DBH \quad (2)$$

Where is the estimated value of the τth quantile of crown diameter at diameter of breast height (DBH), the parameters and from the quantile regression were obtained by minimizing the sum of absolute residual expressed as:

$$\hat{\beta}_\tau = argmin_{\beta \epsilon R^2} \sum_{i=1}^{n} \rho_\tau (y_i - x'_i \beta) \quad (3)$$

Where = parameter and ; **τ** = quantiles. Different quantiles were used including 0.3, 0.45, 0.5, 0.55 and 0.60 were considered.

Linear Mixed Model (LMM)

In contrast to OLS and QR, the linear mixed model accounts for both within and between plot variations. LMM has both fixed and random parameters. Two model forms were considered in this study. In the first LMM form (hereafter called LMM1), the intercept (a) was assumed to vary between plots while the slope (b) coefficient was fixed, expressed as:

$$CD_{\kappa i} = (b_0 + a_\kappa) + b_1 DBH_{ki} + \epsilon_{ki} \quad (4)$$

Where is the random component. The covariance between trees i and i' of plot k is given by:

$$cov(a_\kappa + \epsilon_{\kappa i}, a_\kappa + \epsilon_{ki'}) = cov(a_\kappa, a_\kappa) + cov(a_\kappa, \epsilon_{ki'}) + cov(a_\kappa, \epsilon_{ki}) + cov(\epsilon_{\kappa i}, \epsilon_{\kappa i'}) = var(a_\kappa) = \sigma_a^2 \quad (5)$$

In the second LMM form (hereafter called LMM2), both the intercept and slope were assumed to vary between plots (Eq. 6).

$$CD_{\kappa i} = (b_0 + a_\kappa) + (b_1 + c_\kappa) DBH_{ki} + \epsilon_{ki} \quad (6)$$

Where and are the random component, i.e., plot effects which have multivariate normal distributions with zero mean and variance-covariance matrix (D) defined as:

$$D = var\begin{pmatrix} a_k \\ c_k \end{pmatrix} = \begin{pmatrix} var(a_K) & cov(a_K, c_K) \\ cov(a_K, c_K) & var(c_K) \end{pmatrix} \quad (7)$$

Other parameters and variables are previously defined. Analysis was carried out in R (R Core Team 2017).

Model assessment and validation

In this study, both quantitative and qualitative analyses were used to assess the different modelling methods. Quantitative assessment includes the use of adjusted coefficient of determination (R^2_{adj}), efficiency index (EI), root mean square error (RMSE), mean absolute bias (MAB), relative mean absolute error (RMA) and Akaike Information Criterion (AIC). Methods with high R^2_{adj} and low EI, RMSE, MAB, RMA and AIC were regarded as good. Quali-

Table 2 - Estimated parameters from ordinary least square (OLS), quantile regressions (QR) and linear mixed models (LMM) and their fit indices.

Methods				σ		†R2adj	‡EI	‡RMSE	‡MAB	‡RMA (%)	‡AIC
OLS	2.929*	0.159*				0.526	0.472	0.824	0.642	11.21	3533
QR											
30%	2.529*	0.156*				0.390	0.608	0.935	0.724	13.69	3644
45%	2.822*	0.157*				0.512	0.486	0.836	0.647	11.57	3589
50%	2.889*	0.159*				0.525	0.473	0.825	0.641	11.27	3600
55%	2.991*	0.158*				0.524	0.474	0.826	0.646	11.17	3627
60%	3.012*	0.163*				0.510	0.489	0.838	0.661	11.23	3669
Mixed											
LMM1	2.881*	0.161*	0.768	0.302		0.597	0.401	0.760	0.586	10.21	3414
LMM2	2.939*	0.159*	0.750	0.578	0.033	0.622	0.377	0.736	0.571	10.01	3385

* means significant at 5%; † means the larger the value the better the method; ‡ means the smaller the value the better the method; Joint test of equality of slopes for the quantiles = 0.342

tative assessment was done by visual observation of the residual graphs of the different methods for the validation data set.

$$R^2_{adj} = 1 - \frac{(n-1)}{(n-p)} \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \quad (8)$$

$$EF = \frac{\sum_{i=1}^{n}(yi - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \quad (9)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}} \quad (10)$$

$$MAB = \frac{\sum_{i=1}^{n}|y_i - \hat{y}_i|}{n} \quad (11)$$

$$RMA(\%) = \frac{\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{\hat{y}_i}\right|}{n} x100 \quad (12)$$

$$AIC = -2 \log lik + 2p \quad (13)$$

Where: n = sample size, p = number of parameters; = average tree height; Y_i is the observed value and is the theoretical value predicted by the model. The models were also validated using independent data set (i.e., test data).

Results And Discussion

Crown diameter-stem diameter model

The estimated parameters and fit indices from ordinary least squared (OLS), quantile regression (QR) and linear mixed model (LMM) for modelling the relationship between crown diameter (CD) and DBH of *T. grandis* are presented in Table 2. The results show that all methods had positive intercept which lied between the range of 2.5 and 3.5. This is expected for CD-DBH relationship in most tree species. Hemery et al. (2005) reported positive intercepts (0.6 – 2.8) for CD-DBH relationship in 11 temperate species. Although in some exceptional cases the intercept could be negative which is akin to the Dawkins's "type 3 behaviour". For example, Foli et al. (2003) reported a nonsignificant negative intercept for *Entandrophragma angolense* C. DC. among other tropical tree species investigated. The positive intercept has management implication as it suggests that "the stand basal area could be allowed to increase towards maturity because CD-DBH ratio decreases with stem size" (Foli et al. 2003). The slope values for OLS, median regression (QR at 50%) and linear mixed model with random intercept and slope (LMM2) were approximately the same (0.159 up to 3 decimal places). In addition, QR provides detailed information on the prediction of the response variable compared to OLS. For example, if multiple quantiles were to be considered, 0.05 to 0.95 say, the different/similar slope values from these quantiles will give an indication of heteroscedasticity/homoscedasticity (Koenker and Hallock 2001). In this study, the slope values of the five quantiles indicated homoscedasticity. Also, the joint test of equality of slopes for the five quantiles was not significant at 5% level (p = 0.432)

The quantitative assessment of the methods showed that LMM2 had the highest R^2_{adj}, and least EI, RMSE, MAB, RMA and AIC values. Furthermore, the loglikelihood ratio tests of LMM2, LMM1 and the base model (LMM2 vs LMM1, LMM2 vs OLS and LMM1 vs OLS) were significant at 5% level (not documented). OLS and median regression were relatively the same. The performance of linear mixed model is not unexpected. This method has both fixed and random effects parameters which account for covariate effects (DBH) and heterogeneity be-

Table 3 - Evaluation of the methods using validation data set.

Methods	EI	RMSE	MAB	RMA (%)
OLS	0.579	0.9078	0.6927	12.10
Quantiles				
30%	0.716	1.0091	0.7480	14.19
45%	0.593	0.9186	0.6934	12.42
50%	0.580	0.9087	0.6910	12.16
55%	0.581	0.9095	0.6973	12.05
60%	0.597	0.9216	0.7127	12.11
Mixed Model				
LMM1	0.507	0.8493	0.6350	11.07
LMM2	0.482	0.8279	0.6239	10.89

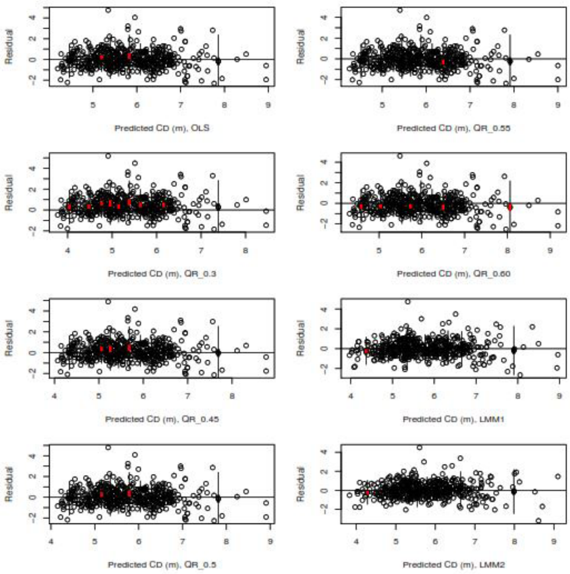

Figure 2 - Plot of residual against predicted values from OLS, QR and LMM using validation data set.

tween plots (De-Miguel et al. 2012, Sun et al. 2017). This method has also been reported to be effective in modelling several tree growth variables (e.g., De-Miguel et al. 2012, Bohora and Cao 2014, Raptis et al. 2018).

The performance of LMM2 was still better than other methods with respect to the validation data set (Table 3). Its efficiency index (EI), root mean square error (RMSE), mean absolute bias and relative mean absolute error (RMA) values were the least. Furthermore, residual trend was assessed by plotting the residuals and predicted CD in 10 classes using validation data set (Fig. 2). Thin and thick lines corresponding to the class-specific standard deviation and 95% confidence interval, respectively were added to the class means. The red colours are thick lines that do not intersect the horizontal line and as such, indicate poor prediction. Only in the first class did LMM performed poorly while OLS and QR (50) predicted poorly in the 4 and 5th classes. In addition, the thin lines did not show heteroscedasticity as function of CD, as such the constant variance assumption was not violated.

Application of CD-DBH relationship

One important application of CD-DBH relationship to forest management is the determination of sustainable thinning regimes/schedules. Hemery (2005) asserted that such thinning schedules are usually built on average diameter (DBH) of the stand to be realized. The estimated parameters from ordinary least square (OLS), quantile regression (0.5) (QR) and linear mixed models (LMM) with random intercept and slope were further applied to prescribe thinning regime for the *T. grandis* plantation in Omo Forest Reserve. Table 4 shows the estimated crown diameter (CD), CD-DBH ratio (R), crown area (CPA), number of trees per ha (10000/CPA), stand basal area (10000 x (π/4)/R^2) and the average spacing required (Sp). From the table, different thinning regimes can be considered. For example, if an average DBH of 25 cm is considered for the *T. grandis*, the expected crown diameter would be 6.9 m, 6.9 m and 6.8 m, predicted from OLS, QR and LMM methods, respectively. Estimations from LMM would be addressed here since it performed relatively better than OLS and QR methods. Thus, given an average crown diameter of 6.8 m, it would occupy an equivalent area 36.32 m^2. And to avoid inter-tree-crown competition (for space, light, etc.) in the stand when DBH is 25 cm, the stand density (N tree per ha) should not exceed 275 Nha^{-1}. This is the limiting density needed for complete canopy (Foli et al. 2003).

Furthermore, supposing the trees are thinned and clear-felled when mean DBH is 50 cm, the expected crown diameter would be 10.5 m and the area occupied would be 86.59 m^2. The stand density remaining after thinning would be 115 Nha^{-1} with an average growing space of 9.3 m. The growing space was obtained from the square root of the ratio of 1

Table 4 - Stand characteristics of the mahoe plantation at LCS in each inventory, showing mean values with standard errors when applicable.

	Ordinary Least Square (OLS)						Quantile (0.5) regression (QR)						Linear Mixed Model (LMM)					
DBH cm	CD m	R	CPA m2	N ha-1	G ha-1	Sp m	CD m	R	CPA m2	N ha-1	G ha-1	Sp m	CD m	R	CPA m2	N ha-1	G ha-1	Sp m
10.0	4.5	45.00	15.90	628	3.88	4.0	4.5	45.00	15.90	628	3.88	4.0	4.6	46.00	16.62	601	3.71	4.1
15.0	5.3	35.33	22.06	453	6.29	4.7	5.3	35.33	22.06	453	6.29	4.7	5.3	35.33	22.06	453	6.29	4.7
20.0	6.1	30.50	29.22	342	8.44	5.4	6.1	30.50	29.22	342	8.44	5.4	6.1	30.50	29.22	342	8.44	5.4
25.0	6.9	27.60	37.39	267	10.31	6.1	6.9	27.60	37.39	267	10.31	6.1	6.8	27.20	36.32	275	10.62	6.0
30.0	7.7	25.67	46.57	214	11.92	6.8	7.7	25.67	46.57	214	11.92	6.8	7.5	25.00	44.18	226	12.57	6.7
35.0	8.5	24.29	56.75	176	13.31	7.5	8.5	24.29	56.75	176	13.31	7.5	8.3	23.71	54.11	184	13.97	7.4
40.0	9.3	23.25	67.93	147	14.53	8.2	9.3	23.25	67.93	147	14.53	8.2	9.0	22.50	63.62	157	15.51	8.0
45.0	10.1	22.44	80.12	124	15.6	9.0	10.0	22.22	78.54	127	15.91	8.9	9.8	21.78	75.43	132	16.56	8.7
50.0	10.9	21.80	93.31	107	16.53	9.7	10.8	21.60	91.61	109	16.83	9.6	10.5	21.00	86.59	115	17.81	9.3
55.0	11.7	21.27	107.51	93	17.36	10.4	11.6	21.09	105.68	94	17.66	10.3	11.3	20.55	100.29	99	18.60	10.1
60.0	12.5	20.83	122.72	81	18.1	11.1	12.4	20.67	120.76	82	18.38	11.0	12.0	20.00	113.10	88	19.63	10.7
65.0	13.3	20.46	138.93	71	18.76	11.9	13.2	20.31	136.85	73	19.04	11.7	12.8	19.69	128.68	77	20.26	11.4
70.0	14.1	20.14	156.15	64	19.36	12.5	14.0	20.00	153.94	64	19.63	12.5	13.5	19.29	143.14	69	21.11	12.0
75.0	14.9	19.87	174.37	57	19.89	13.2	14.8	19.73	172.03	58	20.18	13.1	14.3	19.07	160.61	62	21.60	12.7
80.0	15.7	19.62	193.59	51	20.4	14.0	15.6	19.50	191.13	52	20.65	13.9	15.0	18.75	176.71	56	22.34	13.4
85.0	16.5	19.41	213.82	46	20.85	14.7	16.4	19.29	211.24	47	21.11	14.6	15.7	18.47	193.59	51	23.02	14.0
90.0	17.3	19.22	235.06	42	21.26	15.4	17.2	19.11	232.35	43	21.51	15.2	16.5	18.33	213.82	46	23.38	14.7
95.0	18.1	19.05	257.30	38	21.64	16.2	18.0	18.95	254.47	39	21.87	16.0	17.2	18.11	232.35	43	23.95	15.2

CD = crown diameter, CPA = crown projection area, N= number of tree per ha, G = basal area per ha; R = CD/DBH(m); Sp = Spacing

hectare of an area to the survival number of trees per ha (Hafley and Buford 1985). However, if the stand will be thinned to a final crop and clear-fell when the mean DBH of the forest stand is 75 cm (this is possible if the objective of management is for timber production), it would occupy an area of 160.61 m^2. The number of stems per ha remaining would be 62 Nha^{-1}. The estimated growing space in Table 4 was based on two assumptions – circular tree crown and non-overlapping crown. Foli et al. (2003) stated that such assumptions are possible for well-managed monoculture stand. The *T. grandis* plantation used in this study is a monoculture stand that has been managed for more than a decade specifically for timber production.

T. grandis tree is a fast-growing tropical hardwood species that grows to a height of 39.6 m and DBH of more than 50 cm in well-managed undisturbed stand (Robertson 2002). The average DBH of *T. grandis* data used in this study was 17.9 cm and the predicted CD was 5.7 m (estimated from LMM2). The estimated stocking density (N), basal (G) and growing space (Sp) for the stand would be 307 Nha^{-1}, 7.75 m^2ha^{-1} and 5.7 m, respectively. Other applications of crown diameter-DBH relationship include determination of tree spacing/planting distance for agroforestry project, free growth, managing shelterwood systems, etc. In agroforestry for example, planting distance is predetermined from the commencement of the project. This distance can be determined from the CD-DBH model as the average growing space. The growing space requirement for different sizes were estimated (see Table 4).

Hemery et al. (2005) applied the OLS approach to prescribe thinning decision for *Fraxinus excelsior* L. They estimated 65 Nha^{-1} for the stand after the trees have been thinned to final crop and clear-felled when the mean DBH was 65 cm. The OLS performed relatively well in this study. However, this approach tends to violate the assumption of independence and ignores the plot-crown diameter variation. Thus, predictions from such approach may need to be applied with caution. Also, Zhang et al. (2005) reported poor self-thinning line with OLS method. In the case of linear mixed model (LMM2), the within plot variation is adequately accounted for and as such, provides reliable prediction. The quantile regression was equally good as its predictions were comparable to OLS and LMM2. One advantage of quantile regression is that it provides estimation to any part of a response distribution without restriction on the assumption of the error term. It also provides robustness and is insensitive to outliers (Hao and Naiman 2007, Sun et al. 2017). The quantile regression has been found to be effective in modelling stem diameter percentiles and stand density index (Mehtätalo et al. 2008, Ducey and Knapp 2010).

Conclusion

This study has assessed the relationship between tree crown diameter and diameter at breast height (CD-DBH) of *T. grandis* stand in Omo Forest Reserve, Nigeria using different modelling methods. Of the methods considered, linear mixed model had the best fit. However, when prediction at different percentiles of the crown diameter is of interest, then quantile regression is recommended. The CD-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. This information would help in the sustainable management of the *T. grandis* plantation in the Forest Reserve.

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