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APPLICATION DE LA MÉTHODE *BDq* / LE POINT SUR...

Application of *BDq* method to complex tropical mixed forest ecosystems in Nigeria

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Photo 1.
Tropical mixed forest ecosystem in Nigeria.
Photo F. N. Ogana.

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RÉSUMÉ

Application de la méthode *BDq* dans les écosystèmes tropicaux à forêt mixte complexe au Nigeria

L'absence de pratiques de gestion et de traitements sylvicoles dans les forêts tropicales mixtes complexes du Nigeria conduit à leur exploitation incontrôlée et au déclin de leur biodiversité. Pour assurer le maintien de la production, de la protection et de la conservation de ces peuplements mixtes complexes, la présente étude propose l'application d'une méthode de sélection, dite méthode *BDq* (*B* : surface terrière ; *D* : diamètre maximal ; *q*-ratio) pour leur gestion. Un essai pilote a porté sur deux strates, comportant 15 parcelles pour la strate 1 et 7 parcelles pour la strate 2, chacune avec une superficie de 0,25 ha. Seuls les arbres avec un diamètre à hauteur de poitrine D ≥ 10,0 cm ont été pris en compte pour cette étude. La récolte de bois avec la méthode *BDq* a été quantifiée selon l'intensité d'exploitation, avec *B* à 20 m^2, 25 m^2 et 30 m^2/ha correspondant respectivement à un régime intensif, modéré et peu intense, pour un diamètre *D* à 65 cm. Le *q*-ratio a été calculé pour chacune des parcelles. Les résultats montrent que les trois régimes *BDq* prescrits (intensif, modéré et peu intense) permettent des intensités d'abattage (FI) raisonnables, en pourcentage du volume extrait (V_{ext}) et de la biomasse (W_{ext}). V_{ext} et FI pour la strate 1 varient entre 39,94-62,30 m^3/ha et 11,22-18,18 % et entre 30,44-51,33 m^3/ha et 10,02-17,57 % pour la strate 2. Pour la biomasse, W_{ext} et FI varient entre 18,46-29,82 t/ha et 9,40-15,95 % pour la strate 1 et entre 14,16-24,82 t/ha et 9,73-17,50 % pour la strate 2. Ces constats indiquent que l'application de la méthode *BDq* dans les forêts tropicales mixtes et complexes du Nigeria permettrait d'obtenir des peuplements intéressants.

Mots-clés : gestion sylvicole à couvert continu, peuplements forestiers naturels, surface terrière résiduelle, traitement sylvicole, bois, distribution de Weibull, Nigeria.

ABSTRACT

Application of the *BDq* method to complex tropical mixed forest ecosystems in Nigeria

The absence of management practice/ silvicultural treatments in the complex tropical mixed forests of Nigeria has led to uncontrolled logging in natural forest stands and loss of biodiversity. To sustain production, protection and conservation in these complex tropical mixed stands, this study proposes the application of a selection method – the *BDq* method (*B*: basal area, *D*: maximum diameter, *q*-ratio) to manage these stands. Two strata were used as a pilot test: stratum 1 consisted of 15 plots and stratum 2 of 7 plots, each with an area of 0.25 ha. Only trees with a diameter at breast height (d) ≥ 10.0 cm were considered in this study. Harvesting with the *BDq* method was quantified, by setting *B* at 20 m^2, 25 m^2 and 30 m^2/ha corresponding respectively to heavy, medium and light harvesting regimes. *D* was set at 65 cm and the *q*-ratio was computed for each plot. The results showed that the three *BDq* regimes prescribed (heavy, medium and light) yielded reasonable felling intensities (FI), derived as the percentage of extracted volume (V_{ext}) and biomass (W_{ext}). The V_{ext} and FI for stratum 1 ranged from 39.94-62.30 m3/ha and 11.22-18.18%; the results for stratum 2 were 30.44-51.33 m^3/ha and 10.02-17.57%. For biomass, the W_{ext} and FI ranged from 18.46-29.82 t/ha and 9.40-15.95% for stratum 1 and 14.16-24.82 t/ha and 9.73-17.50% for stratum 2. These findings show that applying the *BDq* method to the complex tropical mixed forests of Nigeria would yield attractive stands.

Keywords: continuous cover forestry, natural forest stands, residual basal area, silvicultural treatment, timber, Weibull distribution, Nigeria.

RESUMEN

Aplicación del método *BDq* a los ecosistemas forestales mixtos tropicales complejos de Nigeria

La ausencia de prácticas de gestión y tratamientos silvícolas en los complejos bosques mixtos tropicales de Nigeria ha provocado la tala incontrolada en las masas forestales naturales y la pérdida de biodiversidad. Con el objetivo de favorecer la producción, la protección y la conservación de estas complejas masas mixtas tropicales, este estudio propone la aplicación de un método de selección —el método *BDq* (*B*: área basal, *D*: diámetro máximo, *ratio q*)— para gestionarlas. Se utilizaron dos estratos como prueba piloto: el estrato 1 constaba de 15 parcelas y el estrato 2, de 7 parcelas, cada una con una superficie de 0,25 ha. En este estudio sólo se consideraron los árboles con un diámetro a la altura normal (D) ≥ 10,0 cm. Se cuantificó el aprovechamiento maderero con el método *BDq*, fijando *B* en 20 m^2/ha, 25 m^2/ha y 30 m^2/ha, correspondientes respectivamente a los regímenes de cosecha intensiva, media y ligera. *D* se fijó en 65 cm y se calculó el ratio *q* para cada parcela. Los resultados mostraron que los tres regímenes de *BDq* prescritos (intensivo, medio y ligero) dieron lugar a intensidades de tala (FI) razonables, derivadas del porcentaje de volumen extraído (V_{ext}) y de la biomasa extraída (W_{ext}). El V_{ext} y el FI del estrato 1 obtenidos fueron de 39,94-62,30 m^3/ha y 11,22-18,18 %; los resultados del estrato 2 fueron de 30,44-51,33 m^3/ha y 10,02-17,57 %. En cuanto a la biomasa, el W_{ext} y el FI obtenidos fueron de 18,46-29,82 t/ha y 9,40-15,95 % para el estrato 1, y 14,16-24,82 t/ha y 9,73-17,50 % para el estrato 2. Estos resultados muestran que la aplicación del método *BDq* a los complejos bosques mixtos tropicales de Nigeria permitiría obtener producciones de masas forestales interesantes.

Palabras clave: silvicultura de cobertura continua, masas forestales naturales, área basal residual, tratamiento silvícola, madera, distribución de Weibull, Nigeria.

Introduction

The tropical rain forest is one of the most diverse biomes of the world (Dupuy *et al.*, 1999; Turner, 2001). It is characterised by multiple species composition and multi-layered structure (Temesgen *et al.*, 2014). Such complex ecosystems provide a wider array of benefits and can address some ecological and environmental issues compared to monoculture stands (Schütz *et al.*, 2012). To sustain production, protection and conservation in the tropical forest ecosystem, there is a need to adopt effective management practice(s). Up to the present time, there is little or no management practice/ silvicultural treatments in the complex tropical mixed forests of Nigeria. This is evidence in the uncontrolled exploitation of natural forest stands in the country.

A well-known management system that will ensure the sustainability of production, protection and conservation in the tropical mixed forest stand is Continuous Cover Forestry (CCF). CCF is a management system that is "characterised by selective harvesting and natural regeneration" (Schütz *et al.*, 2012). Its operability is based on certain principles which include: *continuous cover* (avert large clear-felling), *stability* (sustain stable forest structure) and *naturalness* (biodiversity) (Davies *et al.*, 2008). Mason *et al.* (1999) asserted that to ensure continuous cover, trees on stand › 0.25 ha should not be completely harvested. The benefits of managing forest stand under the CCF systems include but not limited to improve ecological resilience, maintain the biodiversity of habitats, enhance the stands capacity to resist climate change, improve carbon sequestration potential, aesthetic and recreational value etc. (Guldin, 2011; von Gadow *et al.*, 2012; Schütz *et al.*, 2012). Despite the importance of the CCF system, the system has not been applied to the forest ecosystems of Nigeria.

The selection method in the CCF systems can best be achieved with the *BDq* method (Guldin, 1991). The "*BDq method refers to the stand structure that can be uniquely determined for any combination of residual basal area (B), maximum retained diameter class (D), and negative exponential constant between diameter classes (q)*" (Guldin, 1991). Under the *BDq* method, the harvest is quantified by specifying values for the residual basal area (*B*), maximum diameter (*D*) and the *q*-factor (*q*). The *B, D* and *q* parameters are then used to derive the target (ideal) stand (Graz and von Gadow, 2005; Guldin, 1991). The distribution of the target stand is then compared to the actual stand; and harvest (allowable cut) is prescribed by the difference between the two stands (Guldin, 1991). Harvest is only permitted for those trees that exceed the diameter distribution of the target stand. The *BDq* has been consistently used in the management of uneven-aged stands in different parts of the world (Guldin, 1991; Baker *et al.*, 1996; Cancino and von Gadow, 2002; Graz and von Gadow, 2005; Brzeziecki and Kornat, 2011; Drozdowski *et al.*, 2014; Sharma *et al.*, 2014).

To date, there is neither any proper management system nor silvicultural treatment been carried out in the complex tropical mixed stands in Nigeria. It is expected that the use of the *BDq* method will help to sustain production, protection and conservation in the complex tropical mixed forest ecosystem of the region. Therefore, the main objective of this study is to evaluate the use of *BDq* method in the management of the complex mixed stand in Nigeria.

Photo 2.
Tropical mixed forest ecosystem in Nigeria.
Photo F. N. Ogana.

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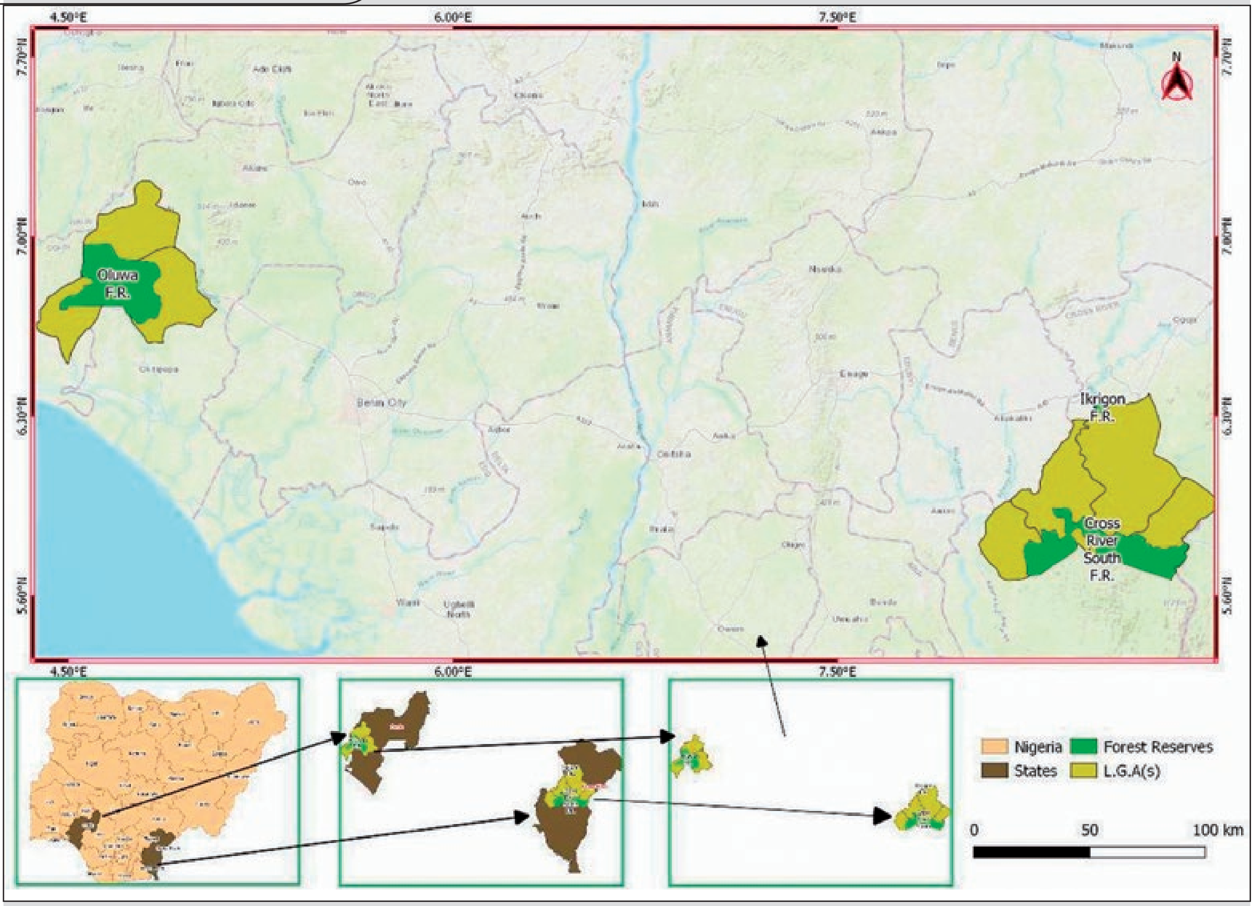

Figure 1.
Location of stratum 1 which consisted of 15 plots systematically demarcated in Ikrigon and Cross River State Forest Reserves (Ikrigon+CRSFR) and stratum 2 comprised of 7 plots demarcated in the natural stand of Oluwa Forest Reserve, Ondo State.

Methodology

Data

The data for the study were collected from two strata located in Cross River State and Ondo State of Nigeria. Both states are within the tropical rain forest zone of the country. Stratum 1 consisted of 15 plots systematically demarcated in Ikrigon and Cross River State Forest Reserves (Ikrigon+CRSFR). Whilst stratum 2 comprised of 7 plots demarcated in the natural stand of Oluwa Forest Reserve, Ondo State (see figure 1). Each plot has an area of 0.25 ha (i.e., 50 m x 50 m). Systematic sampling technique was used for the sample plots. Trees within each plot were identified and enumerated by expert taxonomist to the species level. Flora of West Tropical Africa (Hutchinson *et al.*, 2014) was used for the authentication of the identified species. Only trees with diameter at breast height (d) ≥ 10.0 cm that were considered in this study. Diameters at base and breast of individual tree were measured using a diameter tape while the measurement of tree height was achieved using a vertex. Important stand variables such as the number of trees per ha, basal area per ha, quadratic mean diameter, volume per ha and aboveground biomass in tonnes per ha were computed from the data sets (table I). The individual tree volume was estimated using the volume equations developed for tropical forest trees in Nigeria by Akindele and LeMay (2006). The pan tropical aboveground biomass equation (Chave *et al.*, 2014) was used to estimate the tree biomass. The biomass function requires diameter, height and wood density as input variables. Wood density of individual tree species was retrieved from the global wood density database (Zanne *et al.*, 2009).

Before the application of the *BDq* method, the tree species were classified as timber, non-commercial timber and trees for fruits. The *BDq* method was then applied to the timber species. A list of the commercial timber species is presented in the appendix (tables A.1. and A.2.).

Tree diameter characterisation

Fitting the 3-parameter Weibull function (3P-Weibull)

The 3-parameter Weibull function (3P-Weibull) was used to describe the diameter distribution of the timber species in the complex mixed tropical forest ecosystems. This model is simple and flexible and is more suitable than the 2-parameter Weibull function for describing theoretical uneven-aged (or irregular) truncated stands, namely with a minimum diameter inventory. The probability density function (pdf) and cumulative distribution function (cdf) are expressed as (Gorgoso-Varela and Rojo-Alboreca, 2014):

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} e\left[-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right] \quad [1]$$

$$F(x) = 1 - e\left[-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right] \quad [2]$$

where $f(x)$ is the relative frequency of tree; x represents the continuous random variable (i.e., tree diameter); α is the shape parameter ($\alpha > 0$); β represents the scale parameter ($\beta > 0$); γ is the location parameter. Three frequently used methods were used to fit the 3P-Weibull to the individual plot data from both zones: maximum likelihood (ML), moments (MOM) and percentile. A general adjustment was used for all methods by taking the location (γ) as the minimum observed tree diameter in each plot due the suitability of this value for theoretical distributions with "J reversed" shape.

Maximum likelihood (ML) estimation

The ML estimator defined by equations (3) and (4) was used to estimate the shape and scale parameter of the 3P-Weibull. This method was recently used by Gorgoso-Varela *et al.* (2020):

$$\frac{\sum_{i=1}^{n}(x_i)^{\alpha}\ln(x_i-\gamma)}{\sum_{i=1}^{n}(x_i-\gamma)^{\alpha}} - \frac{1}{\alpha} = \frac{1}{n}\sum_{i=1}^{n}(x_i-\gamma) \quad [3];$$

$$\beta = \left(\frac{1}{n}\sum_{i=1}^{n}(x_i-\gamma)^{\alpha}\right)^{\frac{1}{\alpha}} \quad [4]$$

where x represents tree diameter and n is the number observation in a plot. The LIFEREG procedure in SAS/STAT™ (SAS Institute Inc., 2004) was used to estimate the shape and scale parameters.

Moments

This method is based on the relationship between the parameters of 3P-Weibull and the first and second diameter moment i.e., arithmetic mean and variance, respectively; expressed as equation (5) and (6). This method was recently used by other researchers (Gorgoso-Varela *et al.*, 2020; Pogoda *et al.*, 2020; Sun *et al.*, 2019):

$$\beta = \frac{\bar{d}-\gamma}{\Gamma\left(1+\frac{1}{\alpha}\right)} \quad [5]$$

$$\sigma^2 = \frac{(\bar{d}-\gamma)^2}{\Gamma^2\left(1+\frac{1}{\alpha}\right)}\left[\Gamma\left(1+\frac{2}{\alpha}\right) - \Gamma^2\left(1+\frac{1}{\alpha}\right)\right] \quad [6]$$

where γ represents the location parameter – taken as the smallest diameter of the plot (i.e., 10 cm); $\bar{d}$ is the arithmetic mean diameter; σ^2 is the variance and $\Gamma(\bullet)$ is the gamma function. The bisection iterative procedure (Gerald and Wheatley, 1989) was used to solve equations (5) and (6) in SAS/STAT™ (SAS Institute Inc., 2004).

Percentile

This method is based on the relationship between the parameters of 3P-Weibull and the diameter percentiles. The Dubey (Dubey, 1967) percentile method was used in this study. In this method the scale (β) and shape (α) parameters of the 3P-Weibull function were estimated with the following equations:

$$\beta = P_{63} - \gamma \quad [7];$$

$$\alpha = \frac{ln\left[\frac{ln\,(1-r)}{ln\,(1-t)}\right]}{ln\left[\frac{p_r-\gamma}{p_t-\gamma}\right]} \quad [8]$$

Table I.
Descriptive statistics of the stand variables from the two strata.

Strata	Statistics	N (trees/ha)	G (m^2/ha)	Dg (cm)	V (m^3/ha)	W (tons/ha)
1 (15 plots)	Mean	282	24.1	32.6	515	238
	SD	78	9.1	3.5	209	71
	Minimum	168	11.0	27.3	195	121
	Maximum	440	40.9	39.6	919	372
2 (7 plots)	Mean	278	19.8	29.9	390	162
	SD	57	6.5	2.4	163	73
	Minimum	200	14.5	27.2	267	98
	Maximum	352	31.7	34.5	711	306

N: number of trees per ha; G: basal area per ha; Dg: quadratic mean diameter; V: volume per ha; W: aboveground biomass; SD: standard deviation.

where P_{63} is the diameter corresponding to the 63rd percentile; γ is location parameter; r is equal 0.97; t is 0.17; p_r and p_t represent the diameters corresponding to the 97th and 17th percentiles, respectively.

Evaluation statistics

The consistency of the 3P-Weibull function fitted with ML, moments and percentile was evaluated with Kolmogorov-Smirnov statistic (Dn), Cramér-von Mises statistic (ω^2), mean square error (MSE) and bias. The smaller value of the evaluation of all statistics indicates a better fit:

$$Dn = max\{max_{1\leq i\leq n_i}[F_n(x_i) - F_0(x_j)], max_{1\leq i\leq n_i}[F_o(x_j) - F_n(x_{i-1})]\} \quad [9]$$

$$\omega^2 = \sum_{i=1}^{n}\left\{\hat{F}(x_i) - \frac{(i-0.5)}{n}\right\}^2 + \frac{1}{12n} \quad [10]$$

$$MSE = \frac{\sum_{i=1}^{n}\left(f(x_i) - f_0(x_i)\right)^2}{n} \quad [11]$$

$$Bias = \frac{\sum_{i=1}^{n}\left(f(x_i) - f_0(x_i)\right)}{n} \quad [12]$$

where $F(x_i)$ and $F_0(x_i)$ are the observed cumulative frequency distribution and theoretical cumulative frequency distribution, respectively; x_i (in cm) represents the diameter (i ranged from 1 to n); n is the number of observations; $f(x_i)$ and $f_0(x_i)$ are the observed and predicted relative frequency of trees, respectively.

The ideal irregular structures and the BDq method

The diameter distribution of uneven-aged forests can be expressed as (Cancino and von Gadow, 2002):

$$N_i = k_0 e^{-k_1 d_i} \quad [13]$$

where N_i represents the number of trees in ith diameter class; d_i is the diameter class midpoint (in cm); k_0 the intercept and k_1 represents the rate of change.

The constant rate of change between successive diameter class is defined by the quotient (q) (equation [14]). It provides information on the characteristics such as steepness or flatness of the inverse J-shaped distribution (Schütz *et al.*, 2012):

$$q = N_{i+1}/N_i \quad [14]$$

Substituting N_i of equation (13) into equation (14) will give equation (15):

$$q = k_0 e^{-k_1(d_i - w)}/k_0 e^{-k_1 d_i} \quad [15]$$

$$\therefore q = e^{-k_1 w} \quad [16]$$

where w (in cm) is the width of the diameter class. Other parameters are previously defined. From equation (14), N_{i+1} can be defined as: $N_i x\, q$. Thus, given a specific value of q and with N_{i+1} known, the number of trees in individual diameter class can be computed (Graz and von Gadow, 2005). This can be achieved with the general expression: $N_i = N_1 \text{ x } q^{(i-1)}$ where N_1 is the number of trees in the largest diameter class (Cancino and von Gadow, 2002).

To quantify the available growing stock for the complex mixed tropical stands with a specified residual basal (B, m²/ha) the following expression that is based on diameter class midpoint (d_i), was applied:

$$B = K_2 \sum_{i=1}^{n} N_i \times d_i^2\,; \;\; where\ K_2 = \pi/40000 \quad [17]$$

Substituting $N_i = N_1 \text{ x } q^{(i-1)}$ into equation (17) give:

$$B = K_2 \sum_{i=1}^{n} N_1 \times q^{(i-1)} \times d_i^2 \quad [18];$$

which when rearrange will give:

$$B = N_1 \times K_2 \sum_{i=1}^{n} q^{(i-1)} \times d_i^2 \equiv N_1 \times K_3;\ where\ K_3 = K_2 \sum_{i=1}^{n} q^{(i-1)} \times d_i^2 \quad [19]$$

If $B = N_1 \text{ x } K_3$; then $N_1 = B/K_3$. Thus K_3 is also relevant in the computation of the diameter distributions.

Specifying the residual basal area (*B*, m²/ha), maximum diameter (*D*, cm) and *q*-ratio for the tropical mixed forest

Under the *BDq* method, the harvest is often specified first by defining: the residual basal area per ha (B, m²/ha), maximum diameter (D, cm) and q-ratio (i.e., the quotient). In this study, three *BDq* regimes were evaluated for the tropical mixed forests based on the residual basal area (B, m²/ha). Since there are no previous studies in this region to support the choice of residual basal, B was intuitively set at 20, 25 and 30 m²/ha corresponding to heavy, medium and light-harvesting regimes, respectively. For beech (*Fagus sylvatica* L.) stands in Central Europe Schütz *et al.* (2016) proposed closely values of 20 and 24 m²/ha. The proportional residual basal area B corresponding to the managed trees (timber species) was used for the calculations. This is to minimise overexploitation in as much only moderate allowable cut will be possible in the smaller diameter class. Since the minimum harvesting diameter for industrial roundwood is between 30 and 35 cm (Dupuy *et al.*, 1999), the maximum diameter (D) was set at 65 cm for the tropical forest. This is the diameter beyond which it is expected that a tree should not be considered for timber purpose. Such commercial timber trees with diameter › D, will be retained under the ecological system called "Green Tree Retention (GTR)" (Vanha-Majamaa and Jalonen, 2001). Other non-timber species such as *Ricinodendron heudelotii* (Baill.) Heckel, *Parkia bicolor* A. Chev., *Diospyros crassiflora* Hiern will also be managed under GTR.

The quotient (q) was computed for each plot from the tropical forest data as the arithmetic mean of the values obtained from two successive diameter classes. A large value (≥ 1.69) will yield a high ratio of small trees to larger ones – implies the production of smaller sawn-timber. Whilst a small value (≤ 1.1) will produce a low ratio of small trees to larger ones – implies the production of larger sawn-timber (Guldin, 1991).

Application of the *BDq*: the felling intensity (FI), volume (*V*, m³/ha) and biomass (*W*, tons/ha) to extract

Diameter distribution of the target (i.e., ideal) stand derived was compared by the *BDq* parameters and the actual distribution derived from the inventory data. The difference between the two distributions was used to determine the number of trees per ha to extract from the stand (Guldin, 1991) and the corresponding volume and biomass. To ensure sustainability, the felling intensity (FI) was defined as:

$$FI = \begin{Bmatrix} \dfrac{\sum_{i=1}^{n}(N_i - N_{(i+1)t})P_i}{P_t} & ; & if\ (N_i - N_{(i+1)t}) > 0 \\ 0 & ; & Otherwise \end{Bmatrix}$$

[20]

where FI is the felling intensity; N_i represents the number of trees per ha in diameter class in actual diameter distribution; $N_{(i+1)t}$ number of trees per ha in diameter class directly higher to *i* in the target (ideal) diameter distribution; P_i represents the product (i.e., volume or biomass) of diameter class *i* and P_t represents the total actual products (volume or biomass).

Results and discussion

The descriptive statistics of the estimated location (γ), scale (β) and shape (α) parameters of the Weibull distribution by maximum likelihood, moments and percentiles are presented in table II. The computed Weibull location parameter was the same for all methods because the parameter was taken as the minimum observed diameter per inventory plot. The mean values of the location parameter for stratum 1 (Ikrigon+CRSFR) and stratum 2 (Oluwa FR) were 10.8467 and 10.4428, respectively. This parameter marks the beginning of the diameter distribution. A similar adjustment has been used to achieve good performance with Weibull distribution in the tropical rain forest zone (Ogana *et al.*, 2015; Ogana and Gorgoso-Varela, 2015). The estimated scale and shape parameters varied across the estimation methods. The values of the estimated parameters reflect an ideal structure of all-aged natural forest i.e., inverse J-shaped diameter distributions. Of the three parameters of the Weibull distribution, the shape parameter is the most important with respect to the *BDq* method. This is based on the fact that it determines the shape of the diameter distributions. A value of $\alpha \leq 1$ produces an inverse J-shaped (Vinet and Zhedanov, 2011). The mean values of the shape parameter (α) for stratum 2 were within the limit $\alpha \leq 1$ especially, estimates from moments and percentile methods.

Table II.
Parameter values for the Weibull distribution fitted using three estimation methods.

Strata	Method	Par.	Mean	SD	Minimum	Maximum
1 (N=15)	ML	γ	10.8467	1.0343	10.0000	14.0000
		β	20.0789	4.1944	14.5138	29.7753
		α	1.2091	0.2410	0.8387	1.8861
	Moment	γ	10.8467	1.0343	10.0000	14.0000
		β	19.4796	4.5537	13.1217	29.7334
		α	1.1856	0.2818	0.8529	1.9288
	Percentile	γ	10.8467	1.0343	10.0000	14.0000
		β	19.9762	5.8586	12.5420	31.3400
		α	1.1210	0.2448	0.7850	1.7595
2 (N=7)	ML	γ	10.4428	0.3047	10.0000	10.9000
		β	14.0344	1.9001	11.6868	17.6960
		α	1.0266	0.0905	0.8854	1.1814
	Moment	γ	10.4428	0.3047	10.0000	10.9000
		β	12.9741	1.9798	10.7358	16.6752
		α	0.9303	0.1489	0.7180	1.1855
	Percentile	γ	10.4428	0.3047	10.0000	10.9000
		β	11.5551	1.9195	9.6640	15.3800
		α	0.9870	0.1188	0.8604	1.1721

Par.: parameter; SD: standard deviation; ML: maximum likelihood.

Table III.
Characterisation of the natural mixed strata considering timber species according to shape parameter *α* of the Weibull distribution fitted by moments.

Strata	Uneven-aged ($\alpha \leq 1$)	Two-aged ($1 < \alpha \leq 1.35$)	Even-aged ($\alpha > 1.35$)	Total plots
1	6 (40%)	5 (33.3%)	4 (26.7%)	15
2	6 (85.7%)	1 (14.3%)	0 (0%)	7

Table IV.
Mean values of Kolmogorov-Smirnov statistic (*Dn*), Cramér-von Mises statistic (ω^2), Mean Squared Error (MSE) and bias.

Strata	Method	D_n	ω^2	MSE	bias
1	ML	0.105788	0.096385	0.000332	0.000186
	Moment	0.105100	0.082868	0.000339	0.000173
	Percentile	0.110735	0.147039	0.000324	0.000824
2	ML	0.115378	0.110994	0.000283	0.000262
	Moment	0.121492	0.079650	0.000311	0.000396
	Percentile	0.122601	0.119634	0.000294	0.000610

Characterisation of the natural stand strata considering timber species according to the shape parameter (α) of the Weibull distribution fitted by moments showed that 40% of the plots was classified as uneven-aged ($\alpha \leq 1$), 33.3% as two-aged i.e., "semi-regular" ($1 < \alpha \leq 1.35$) and 26.7% as even-aged ($\alpha > 1.35$) in stratum 1 (Ikrigon+CSFR) (table III). However, in stratum 2 (Oluwa forest FR), 85.7% of the plots were classified as uneven-aged and 14.3% as two-aged. No plot was in the class of even-aged. It is essential to recognise two-aged stands because they could be changed to uneven-aged without considerable alteration of their present structure.

The result of the evaluation statistics showed that the Weibull distribution fitted by maximum likelihood, moments and percentile performed better in the first stratum (Ikrigon+CRSFR) compared with the second stratum (Oluwa forest) (table IV). The Weibull distribution fitted by moments had the smallest Kolmogorov-Smirnov (Dn) (0.105100) statistic, Cramér-von Mises statistic (ω^2) (0.082868) and bias (0.000173) in stratum 1 (Ikrigon+CSFR) (table IV). It also presented the smallest Cramér-von Mises statistic (ω^2) (0.079650) in the second stratum. The Weibull distribution fitted with Maximum likelihood performed equally well, especially in the second stratum. The Weibull distribution fitted by percentile produced the poorest fits. The estimation method by moments remains one of the simplest procedures for estimating the parameters of the Weibull distributions. The variance and mean diameter required for using moments can be disaggregated from a yield table and apply. A parallel study by Sun *et al.* (2019) also reported good fit with the Weibull function fitted by moment for characterising diameter distributions in uneven-aged mixed stands of pine and oak. In Nigeria, Ogana (2020) also observed that using moment-based estimator to fit the Weibull distribution produced results comparable to other complex estimators. The author evaluated ten estimators used for the Weibull distribution in the study.

The line plots of the mean square error statistic describing the fit of the Weibull distribution fitted by ML, moments and percentile across the diameter classes are presented in figures 2 and 3. The line patterns produced by the Weibull distribution fitted by the three methods were the same – characterised by increasing and decreasing behaviour. However, the MSE declined steadily in the larger diameter classes in both strata.

The mean statistics of the *q*-ratio for the total plots and the uneven-aged plots (i.e., plots considering timber species) in the two strata are shown in table V. The mean values of the *q*-ratio for the uneven-aged plots in stratum 1 and stratum 2 were 1.479 and 1.487, respectively. The ratio will ensure the sustainable production of both sawn-timber in the mixed stands. Guldin (1991) asserted that a larger "*q*-ratio will steepen the ideal (target) distribution, retaining more small trees than larger ones and in consequence, increasing harvesting volume in the mixed stands". An ideal *q*-ratio could be intuitively chosen for a stand depending on the economic policy or management goal (Graz and von Gadow, 2005). However, it is more suitable to compute *q*-ratio for the individual plot, such a procedure will improve accuracy and provide flexibility.

The results of a simulated logging by applying the three regimes of *BDq* to the two strata in which the maximum diameter (*D*) was set at 65 cm and *q*-ratio derived by plot is shown in table VI. The three regimes specified were heavy (20 m^2/ha), medium (25 m^2/ha) and light (30 m^2/ha). For each regime and stratum, the ideal basal area per ha applied ($B_{applied}$) was lower compared with the specification for that regime. The values only correspond to the quantity of timber species in the stratum. Only timber species are managed under the *BDq* method; whilst some species will be retained as GTR, including non-timber and fruit trees. If a heavy *BDq* regime is to be considered for the uneven-aged plots in stratum 1, the number of trees per ha to extract (N_{ext}) is 28.56 N/ha with corresponding volume (V_{ext}) and biomass (W_{ext}) of 62.30 m^3/ha and 29.82 tons/ha, respectively. The required felling intensities in % volume and biomass of the total of the managed species (FI_M) will be 18.18 and 15.95, respectively. In the case of stratum 2 using heavy *BDq* regime,

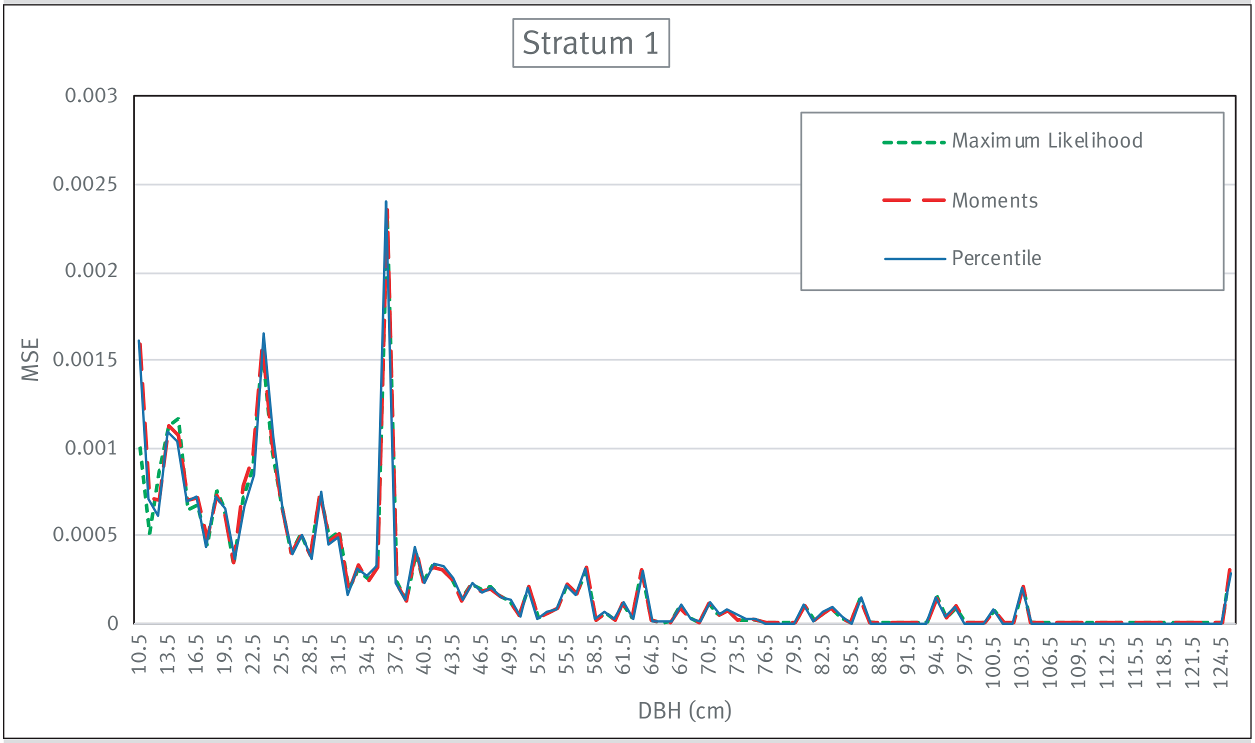

Figure 2.
Behaviour of the MSE for the fits by maximum likelihood, moments and percentile in each diameter class for stratum 1.

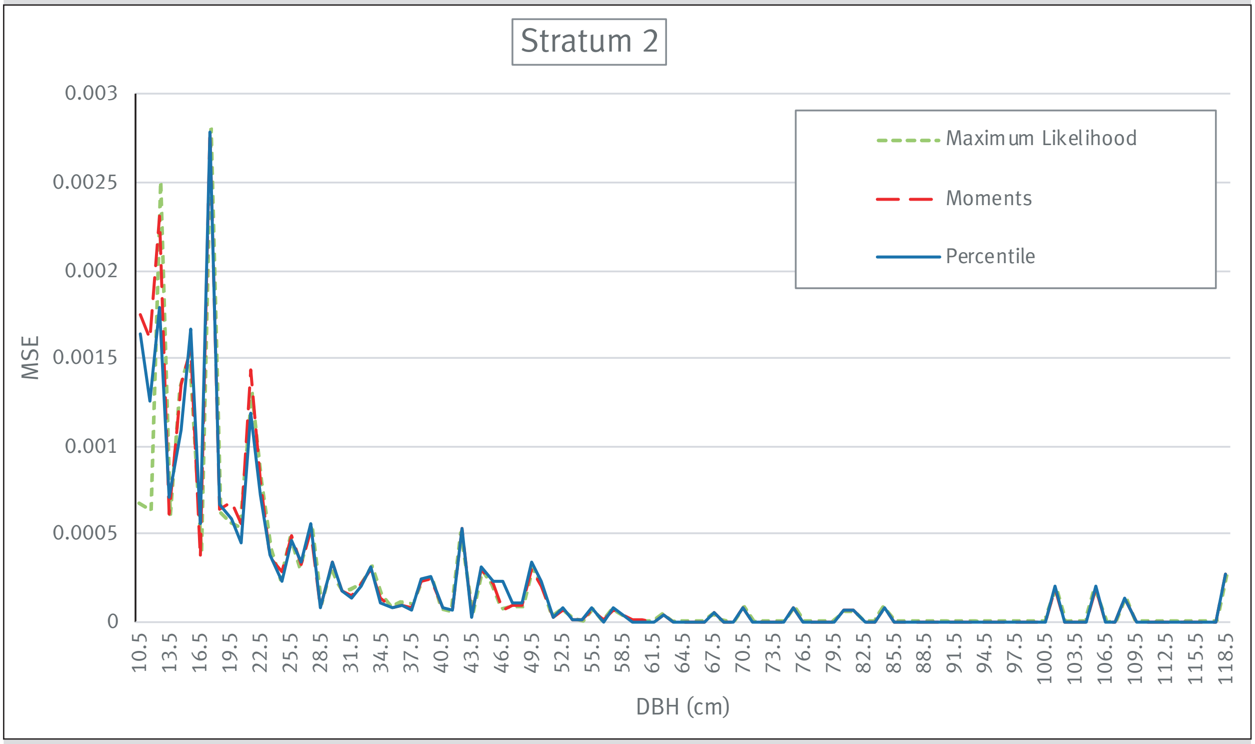

Figure 3.
Behaviour of the MSE for the fits by maximum likelihood, moments and percentile in each diameter class for stratum 2.

Table V.
Mean statistics of the *q* factor for total plots and uneven-aged plots in both strata.

Strata	Mean	SD	Maximum	Minimum
1 (total plots)	1.479	0.150	1.750	1.200
1 (uneven-aged plots)	1.479	0.171	1.678	1.200
2 (total plots)	1.489	0.137	1.778	1.361
2 (uneven-aged plots)	1.487	0.149	1.778	1.361

N_{ext} will equal to 34.60 N/ha and will yield V_{ext} and W_{ext} of 51.33 m³/ha and 24.68 tons/ha, respectively. The FI_M for volume and biomass in the simulated logging will be 17.57 and 17.50, respectively. To our knowledge, this is the first application of the *BDq* method to a complex mixed tropical forest ecosystem, especially in Nigeria.

The graph of the observed and target (ideal) diameter distributions of timber species derived by the applying three regimes of B, with D = 65 cm and *q* computed for each plot in the two strata is presented in figure 4. Four representative plots (2 each from stratum 1 and stratum 2) with the highest density were used. From stratum 1, plot 4 with a *q* factor = 1.43, harvesting is only possible in diameter classes of 37.5, 47.5 and 52.5 cm. The commercial timber species in those classes are *Cola gigantea* A. Chev., and *Gmelina arborea* Roxb. Other commercial timber species such as *Dialium pachyphyllum* Harms, *Dialium guineense* Willd. could also be harvested in the stratum (plot 6). The commercial timber such as *Albizia perrieri* (Drake) R. Vig., *Afzelia africana* Sm., *Dialium guineense* Willd., *Milicia excelsa* (Welw.) C.C. Berg and *Pterocarpus santalinoides* DC. with diameter above D, together with other non-timber species will constitute part of the GTR. Few timber species are available for harvest in stratum 2. Some timber species in the lower diameter class of 22.5 and 27.5 cm could also be harvested for other purposes (e.g. pole) under heavy and medium regimes (treatments) except in stratum 2 plot 1. List of timber species in those classes include *Pterygota bequaertii* De Wild., *Celtis zenkeri* Engl., *Bombax buonopozense* P. Beauv., *Terminalia superba* Engl. & Diels, *Picralima nitida* (Stapf) T. Durand & H. Durand, *Milicia excelsa* (Welw.) C.C. Berg, *Triplochiton scleroxylon* K. Schum., *Malacantha alnifolia* (Baker) Pierre, *Cedrela odorata* L., *Cleistopholis patens* (Benth.) Engl. & Diels, *Antiaris toxicaria* Lesch., and *Hannoa klaineana* Pierre ex Engl.

Adoption of the *BDq* selection method will ensure sustainable management of the mixed stands. And as part of the CCF systems, the method will enhance the stands' capacity to resist climate change, improve carbon sequestration potential, promote better biodiversity of habitats, etc. (Schütz *et al.*, 2012).

Table VI.
Mean values in each stratum after application of three regimes of the *BDq* method for *D* = 65 cm and *q* calculated by plot.

Strata	Regime	B_{Total} (m²/ha)	$B_{applied}$ (m²/ha)	N_{ext} (Pies/ha)	V_{ext} (m³/ha)	FI_M (%V)	FI_T (%V)	W_{ext} (tons/ha)	FI_M (%W)
1 (total plots)	Heavy	20	15.52	69.43	190.66	37.19	30.94	82.05	36.53
	Medium	25	19.41	52.94	166.11	31.47	26.20	70.77	30.77
	Light	30	23.29	41.99	147.07	27.15	22.59	62.32	26.47
1 (uneven-aged plots)	Heavy	20	15.52	28.56	62.30	18.18	14.62	29.82	15.95
	Medium	25	19.41	15.55	47.65	13.68	10.98	22.22	11.63
	Light	30	23.29	9.84	39.94	11.22	8.88	18.46	9.40
2 (total plots)	Heavy	20	14.69	30.36	44.74	15.70	11.69	21.56	15.72
	Medium	25	18.37	18.66	33.84	11.34	8.79	15.97	11.14
	Light	30	22.04	12.49	26.09	8.59	6.77	12.14	8.34
2 (uneven-aged plots)	Heavy	20	14.69	34.60	51.33	17.57	13.32	24.68	17.50
	Medium	25	18.37	21.77	39.48	13.23	10.26	18.63	12.99
	Light	30	22.04	14.57	30.44	10.02	7.90	14.16	9.73

B: residual basal area for the commercial managed species; N_{ext}: number of trees to extract; V_{ext}: volume to extract; FI_M: felling intensity in % volume and biomass of the total of the managed species; FI_T: felling intensity in % of the total volume of species in the stratum (timber, non-timber and trees for fruits); W_{ext}: biomass to extract.

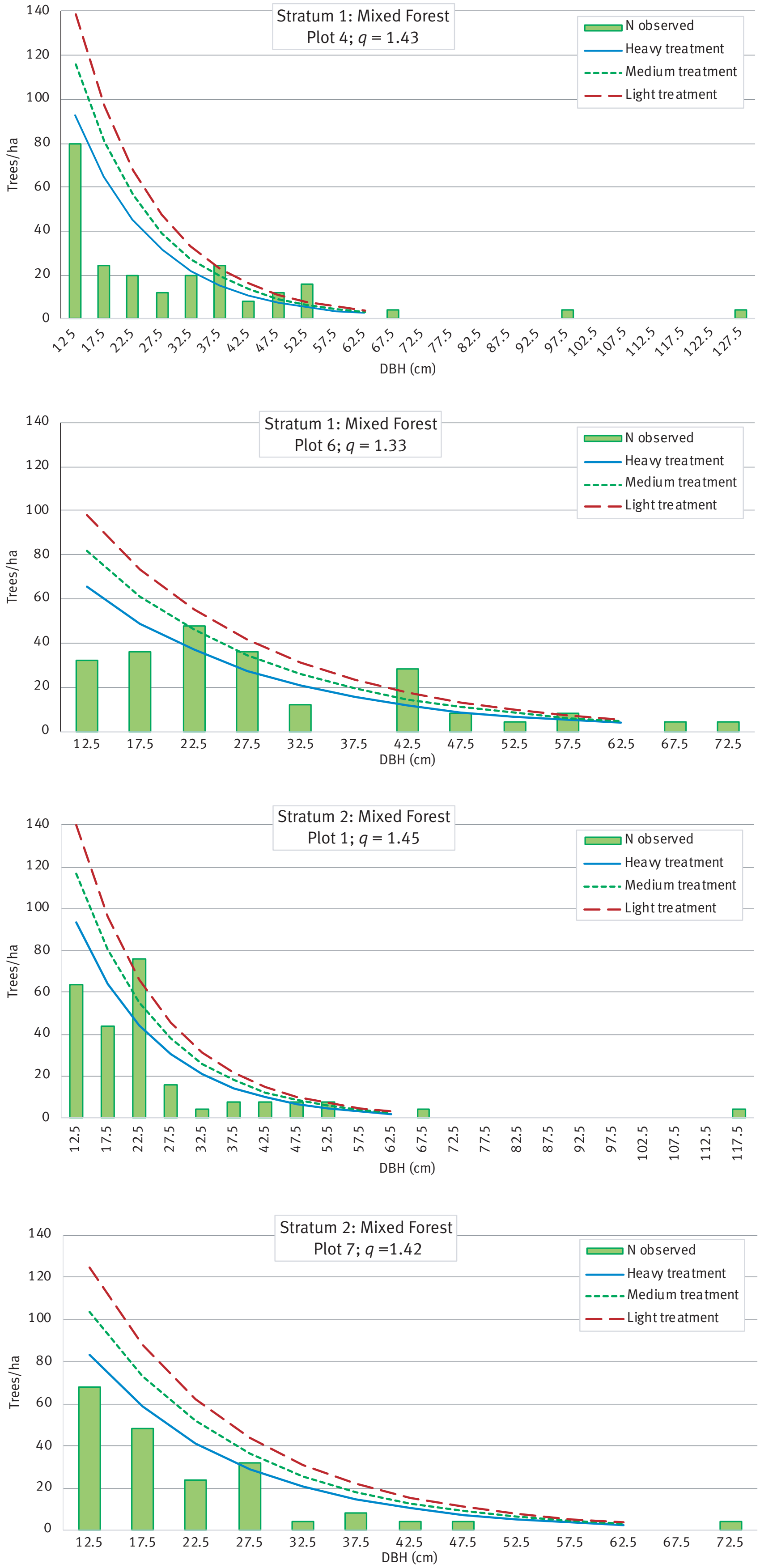

Figure 4.
Observed and ideal diameter distributions of timber species derived by applying *BDq* method for three values of *B*, *D* = 65 cm and *q* computed for the individual plots in the two strata.

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Appendice

Table A.1.
Commercial timber species in stratum 1.

S/N	Species	S/N	Species	S/N	Species
1	*Afzelia africana*	26	*Dialium guineense*	51	*Pterocarpus mibreadii*
2	*Albizia gummifera*	27	*Dialium pachyphyllum*	52	*Pterocarpus osun*
3	*Albizia lebbeck*	28	*Distemonanthus benthamianus*	53	*Pterocarpus santalinoides*
4	*Albizia perrieri*	29	*Dracaena mannii*	54	*Pterocarpus soyauxi*
5	*Albizia zygia*	30	*Entandrophragma cylindricum*	55	*Pterygota macrocarpa*
6	*Allanblackia floribunda*	31	*Funtumia africana*	56	*Pycnanthus angolensis*
7	*Alstonia boonei*	32	*Funtumia elastica*	57	*Spathodea campanulata*
8	*Anthocleista vogelii*	33	*Gmelina arborea*	58	*Staudtia stipitata*
9	*Antiaris toxicaria*	34	*Gossweilerodendron balsamiferum*	59	*Sterculia setigera*
10	*Baillonella toxisperma*	35	*Hylodendron gabunense*	60	*Strombosia pustulata*
11	*Barteria nigritana*	36	*Khaya grandifoliola*	61	*Symphonia globulifera*
12	*Berlinia confusa*	37	*Khaya ivorensis*	62	*Tectona grandis*
13	*Blighia sapida*	38	*Klainedoxa gabonensis*	63	*Terminalia superba*
14	*Borassus aethiopium*	39	*Lannea welwitschii*	64	*Tetrapleura tetraptera*
15	*Brachystegia nigerica*	40	*Lophira alata*	65	*Treculia obovoidea*
16	*Carapa procera*	41	*Lovoa trichilioides*	66	*Uapaca guineensis*
17	*Ceiba petandra*	42	*Margaritaria discoidea*	67	*Uapaca staudtii*
18	*Celtis zenkeri*	43	*Milicia excelsa*	68	*Xylopia aethiopica*
19	*Chrysophyllum giganteum*	44	*Musanga cecropioides*	69	*Zanthoxylum zanthoxyloides*
20	*Cleistopholis patens*	45	*Pausinystalia talbotii*		
21	*Coelocaryon preussii*	46	*Pentaclethra macrophylla*		
22	*Cola gigantea*	47	*Pentadesma butyracea*		
23	*Combretodendron macrocarpum*	48	*Pierreodendron africanum*		
24	*Cylicodiscus gabunnesis*	49	*Piptadeniastrum africanum*		
25	*Daniella ogea*	50	*Pseudospondias microcarpa*		

Table A.2.
Commercial timber species in stratum 2.

S/N	Species	S/N	Species
1	*Afzelia bipindensis*	22	*Lovoa trichilioides*
2	*Albizia ferruginea*	23	*Malacantha alnifolia*
3	*Anthocleista djalonensis*	24	*Mansonia altissima*
4	*Antiaris toxicaria*	25	*Maranthes robusta*
5	*Bombax buonopozense*	26	*Milicia excelsa*
6	*Brachystegia eurycoma*	27	*Mitragyna stipulosa*
7	*Carapa procera*	28	*Musanga cecropioides*
8	*Cedrela odorata*	29	*Nesogordonia papaverifera*
9	*Ceiba pentandra*	30	*Pausinystalia talbotii*
10	*Celtis zenkeri*	31	*Picralima nitida*
11	*Cleistopholis patens*	32	*Pterygota bequaertii*
12	*Cordia millenii*	33	*Pterygota macrocarpa*
13	*Distemonanthus benthamianus*	34	*Pycnanthus angolensis*
14	*Entandrophragma angolense*	35	*Staudtia stipitata*
15	*Entandrophragma cylindricum*	36	*Sterculia rhinopetala*
16	*Ficus mucuso*	37	*Sterculia tragacantha*
17	*Funtumia elastica*	38	*Strombosia pustulata*
18	*Guarea cedrata*	39	*Terminalia superba*
19	*Hannoa klaineana*	40	*Triplochiton scleroxylon*
20	*Khaya ivorensis*	41	*Uapaca heudelotii*

Conclusion

This study has successively applied the *BDq* method to the complex mixed tropical forests of Nigeria. Harvest in the stands was defined using three regimes of residual basal area (20, 25 and 30 m^2/ha) with desirable felling intensities that would ensure the sustainability of the timber species. The number of trees to extract from the stand and the corresponding volume and aboveground biomass by using the *BDq* method were rational. Commercial timber species with a diameter greater than the 65 cm, together with other non-timber and trees for fruits will comprise the GTR system. Thus, with the adoption of *BDq* method more attractive stand will be produced.

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Methodology	F. N. Ogana
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Visualization	F. N. Ogana, J. J. Gorgoso-Varela
Writing – Original Draft Preparation	F. N. Ogana
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