Diameter Distribution Models and Carbon Sequestration Potential of Afi Forest Reserve, Cross River State, Nigeria

Abstract

The ability to predict the distribution of diameters in a stand helps forest managers to make informed decisions such as prescription of silvicultural treatments. This research work developed and validated diameter distribution models and estimated the carbon potential of Afi River Forest, Cross River State, Nigeria. Two transects of 1500m in length with a distance of 500m between the two parallel transects were used for this study. Sample plots of 50m X 50m in size were laid in alternate along each transect at 100m interval totaling 10 sample plots per 1500m transect and a total of 20 sample plots in the study area. A total of 1368 individual tree species spread across 23 species belonging to 18 different tree families were measured for diameter at breast height, diameters at the base, middle and top and tree total height. The mean diameter at breast height (dbh) and total height of 25.8cm and 18.5m were respectively obtained while12.01 m^3 and 80.72 kg were obtained for average tree volume and biomass respectively. At stand level, mean basal area of 48.95m^2ha^{-1} was obtained with a mean volume of 244.561m^3 $ha^{-1}$and mean green biomass was 448.860ton $ha^{-1}$with a dry biomass of 325.423ton ha^{-1}. Easy Fit software was used for Diameter Distribution models. Three diameter distribution models were developed and validated for the reserve. However, Log-Logistic (3P) was the more fitted among the selected diameter models in the reserve. None of the selected model was significant; therefore, fitted models can be used for diameter distribution of the study area.

Keywords: Diameter, Carbon, Systematic sampling, Transect and Reserve

Introduction

Comment [BB1]: This introduction is incomplete. The problem is not clearly defined. At the very least, the study should have been contextualized, with emphasis on the specific features of the area of interest, and a succinct review of the state of research should have been given in order to justify the relevance of this study with a view to providing tools for better silvicultural management.

Diameter at breast height is one of the most important and most applied bioassay variables in forest trees, so, its study is important to describe the structure of any given forest (Bassey and Adekunle, 2022). Diameter distribution and the related statistical models can play an important role in forest science, for example, in some growth modeling, it is necessary to know the type of diameter distribution function and its parameters to identify the appropriate model for it. Diameter distributions can be used to indicate whether the density of smaller trees in a stand is sufficient to replace the current population of larger trees and to help evaluate potential forest sustainability (Bassey and Adekunle, 2022).

Development of growth models for tropical species enables promotion of the productive and protective aspects of diverse species present (Gorgoso*et al.* 2007). Diameter class models allow planning of various uses and provide data about stand structure. These models are used to estimate stand variables and their structure with a density or distribution function, which is fitted to diameter distributions at breast height (dbh) or individual tree volume. Forest managers are interested in being able to estimate the number of trees in different diameter classes in a stand, because the size of the diameter determines the industrial use of the wood and thus the price of the different products. Diameter distributions also provide information about stand structure, age structure, stand stability, thus, enabling the planning of silvicultural treatments.

Diameter distribution functions are of major importance to the forest managers in order to select system that emphasized the importance of recreating a specified diameter distribution or stand structure at the end of each cutting cycle (Gottsacker, 2005).Models that provide accurate estimates of tree growth and yield have become essential tool for evaluating the numerous management and utilization decision in the forestry profession. No single type of growth model can be expected to provide information efficiently for all levels of decision making (Adesoye, 2002). Hence, there is need for wide variety of models of varying degree of complexity for the management of natural forest and plantation. Dbh of forest trees is an essential variable in determining the basal area and more importantly the volume of the forest. It is the easiest measurable variable which can be used to predict or project the growth and yield of the forest ecosystem. Therefore, the main objective of this study is to determine diameter distributions using different distribution functions.

Research Methodology

Study Area

Afi River Forest Reserve is approximately between Latitudes 6^{o} 08´ and 6^{o} 26´N and Longitudes 8^{o} 50´ and 9^{o} 05´E and covers a land area of 383.32 km^{2} including the Afi Mountain. The topography of the study area is extremely complex with many connected ridge systems, isolated peaks and outcrops. It has an altitude range between 200 to 1200m above sea level. Basically, the reserve is characterized by large tracts of rock outcrops especially on the North-East axis. The hills of the reserve are extension of the Cameroon Mountains geological formation. The fast moving and high gradient streams drain the Afi River Forest Reserve, constituting an important watershed.

Comment [BB2]: A map showing the location of the study area would be useful.

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Comment [BB4]: What is the legal status of this forest?

Crustaceous sedimentary sandstone occupies a significant area of the study site, with volcanic eruptions that sometimes comprises columnar basalt in some places (Bassey*et al.*, 2022). Old sedimentary soils tend to be sandy with structure less profiles and incipient laterite. Generally, the soils vary from clayey-loam to loamy-clay and normally red with high content of iron oxide. They are acidic and low in nutrient status, which makes them unsuitable for arable crop production (Bassey *et al.*, 2022) Annual rainfall varies from 3,000 mm to 3,800 mm (Bassey *et al.*, 2022) while the mean annual temperatures are 22.2^{o}C and 27.4o C on Afi mountain and lowland, respectively. Balogun, (2003) indicated that the mean annual relative humidity is 78% at 7.00 Hr. The vegetation of Afi River Forest Reserve generally falls within the tropical high forest vegetation zone. The rainforest occupies the foot of the mountain. At about 700m above sea level, the forest structure changes gradually into sub-montane vegetation, while above 500m, the vegetation have been changed into grassland as a result of annual bush fire.

Sampling Technique and Data Collection

Systematic line transect was used in the laying of sample plots. Two transects of 1500m in length with a distance of at least 500m between the two parallel transects were used for this study. Sample plots of 50m x 50m in size were laid in alternate along each transect at 100m interval; summing a total 10 sample plots per 1500m transect and a total of 20 sample plots in the forest reserves (Stanley and Ajayi, 2024).In each of the sample plot, all living trees with dbh ≥10cm were identified and measured.

Comment [BB5]: 20 plots sampled in a reserve of 383.32 km^{2} seems to me to be too few.

Spiegel relascope was used for individual tree DBH and other diameters (diameter at the base, diameter at the middle and diameter at the top) and tree height measurement. For trees growing on a slope, the dbh was measured from the uphill side of the tree. Importantly, buttresses were considered to be non-commercial. So, when buttresses extending more than 1.30 m above ground surface were encountered, the equivalent of dbh was measured at a height of 20 cm above the upper limit of the buttresses. When knots or localized deformations occurred at breast-height point, a more representative dbh point either above or below the breast-height point was chosen as recommended by Adekunle *et al.*, (2010).

Comment [BB6]: What were these measured parameters used for?

Data Analysis

Basal Area Estimation

The diameter at breast height was used to calculate the basal area.

$$Basal\ Area\ (BA) = \frac{\pi D^2}{4}$$ eq.1

Where: D = diameter at breast height (m), π = 3.14 and BA = Basal Area (m^2).

The mean Basal Area (BA) for each plot was obtained by adding all trees basal area in the plot while mean basal area for the plot was calculated with the formula:

$$\overline{BA_p} = \frac{\Sigma BA}{n}$$ eq.2

where; $\overline{BA_p}$ = Mean basal area per plot

Stem Volume Estimation

Individual tree volume was calculated using the Newton's formula of Husch*et al.*, (2003); Bassey, *et al.*, (2022) given as:

$$V = \frac{h}{6}[A_b + 4A_m + A_t]$$ eq.3

Where: V= Volume (m^3),

A_b = Basal area at the base (m^2),

A_m = Mid basal area (m^2) and A_t = Basal area at the top (m^2)

The plot volumes were obtained by adding the volume of all the trees in the plot while mean plot volume was obtained by dividing the total plot volume by number of sample plots. The volume of trees per hectare (V_{ha}) was subsequently estimated by multiplying the mean per plot by the number of sampling units in a hectare (Stanley and Ajayi, 2024, Adekunle, 2010).

Diameter Distribution Models for Screening

The diameter distribution models were generated using Easy Fit software. The diameter probability functions that were adopted in this study for diameter distribution estimation areas were listed**:**

Weibull model: Ratkowsky (1983) and Myers (1986) employed the two-parameter Weibull models in their studies.

The models were: $W(t) = \left(\alpha - \beta e^{-kt^{m}}\right) + \varepsilon$ eq.4

Logistic model: Nelder (1961) and Oliver (1964) employed this model:

$W(t) = \alpha/(1 + \beta e^{-kt}) + \varepsilon$ eq.5

Burr (4P) $f(x) = \frac{ak\left(\frac{x-y}{\beta}\right)^{a-1}}{\beta\left(1+\left(\frac{x-y}{\beta}\right)^{a}\right)^{k+1}}$eq.6

JohnsonS$_B$ Distribution $f(\mathrm{x}) = \frac{\delta}{\sqrt[\lambda]{2\pi z(1-\mathrm{Z})}} \exp\left[-\frac{1}{2}\left(\gamma + \delta \ln\frac{z}{1-Z}\right)^{2}\right]$ eq.7

Beta Distribution $F(\mathrm{x}) = \frac{1}{B(\alpha_1,\alpha_2)} \frac{(\mathrm{x}-\mathrm{a})^{\alpha_1-1}(\mathrm{b}-\mathrm{x})^{\alpha_2-1}}{(\mathrm{b}-\mathrm{a})^{\alpha_1+\alpha_2-1}}$eq.8

Weibull Distribution $f(\mathrm{x}) = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1} exp\left(-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right)$ eq.9

General Pareto Distribution $f(x) = \frac{1}{\sigma}\left(1 - \frac{\xi(\chi-\mu)}{\sigma}\right)^{\left(-\frac{1}{\xi}-1\right)}$ eq.10

Generalized Gamma 4P Distribution $f(x) = \frac{k(\chi-\gamma)^{k\alpha-1}}{\beta^{k\alpha}\Gamma(\alpha)} \exp\left(-\left(\frac{\chi-\gamma}{\beta}\right)^{k}\right)$ eq.11

Lognormal Distribution $f(x) = \frac{1}{x\alpha\sqrt{\pi}} e0.5^{\left(\frac{lnx-\mu}{\sigma}\right)2}$eq.12

Gamma 3P $f(x) = \frac{x^{\alpha-1}}{\beta\Gamma(\alpha)} \exp\left(\frac{-x}{\beta}\right)$ eq.13

Exponential 2P $f(x) = \lambda e^{-\lambda x}$ eq.14

Erlang 3P $f(x) = \frac{\lambda^k x^{k-1} e^{-\lambda x}}{(k-1)!}$ eq.15

Inverse Gaussian $f(x) = \left(\frac{\lambda}{2\pi x^3}\right)^{1/2} exp\left(\frac{-\lambda(x-\mu)^2}{2\mu^2 x}\right)$ eq.16

Test Statistics for Assessing Diameter Distribution Models

The selection of the best diameter distribution models were based on:

i. Kolmogorov Smirnov
ii. Anderson Darling
iii. Chi-Square

Validation of the Diameter Distribution Models

For diameter distribution models, the values of the estimated parameters were inputted in the Probability Density Function of the models and x was substituted with DBH using the best adjudged model. The results obtained (predicted diameter distribution) were compared with the observed DBH frequency using one-way Analysis of Variance and the Student's T-test of Goulding (1997). The models showing no significant difference between the observed and the predicted DBH were however considered to be suitable in describing the diameter distribution of the species in the study.

Aboveground Green Biomass Estimation

The summation of the biomass that was calculated for all trees in a sample produced the total plot biomass (AGB_{plot}). This per plot estimate of aboveground biomass (in kg) was divided by 1000 to express it in metric tons. This was then converted to per hectare estimate (AGB_{ha}) by using the equation:

$$AGBper\ ha = \left(\frac{Ah}{Ap}\right) \times AGBplot \qquad \text{eq.17}$$

Where: AGBha= aboveground biomass (metric tons per hectare)

Ah= area of one hectare in m^2

Ap= area of the plot (m^2) (Brown, 1997, Bassey and Ajayi, 2024).

To estimate the total biomass of each site, the estimate of biomass of each species was summed up and multiplied with the total size of the forest.

Aboveground Dry Biomass Estimation

Aboveground dry biomass estimation was calculated from:

$$W = \frac{AGBh \times 0.725}{1000} \qquad \text{eq.18}$$

Where: W= aboveground dry biomass (metric tons)

AGB_h = aboveground green biomass (kg ha^{-1}) expressed metric ton

(Chaven and Rasal *et al.*, (2010)

Determination of Carbon Sequestration

$$Sc = Wx\ 0.5 \qquad \text{eq.19}$$

Where; Sc = sequestered carbon (tha^{-1})

W= aboveground dry biomass (t ha^{-1}) (Bassey and Ajayi, 2020) and expressed in t/ha.

RESULTS

Growth Characteristics of Afi River Forest Reserve

Results in table 3 below show that a total of 1368 individual trees spread across 65 species belonging to 18 different tree families were measured for diameter at breast height, diameters at the base, middle and top and tree total height. The mean diameter at breast height (dbh) and mean total height of 25.82 cm and 18.5m respectively were obtained while10.36 m^3 and 76.31 kg were obtained for average tree volume and biomass respectively. Mean basal area of 50.29 m^2 ha^{-1} was estimated with a mean volume of 271.249 m^3 ha^{-1} and mean green biomass was 460.867ton $ha^{-1}$with a mean dry biomass of 334.128ton ha^{-1}.

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Table 1: Summary of Characteristics data for Afi River Forest Reserve

S/N	Parameters	Mean	Min.	Max.	Std. Error	Std. Deviation	Skewness	Kurtosis
1	No. of sample plots measured	20						
2	No of trees measured	1368						
3	DBH(cm)	38.47	3.00	193.80	0.7883	26.03	3.11	12.27
4	Height (m)	18.6	11.40	46.20	0.55	19.14	2.72	6.84
5	Basal area. (m^2 ha^{-1})	48.95	36.68	58.46	1.22	5.500	1.386	2.123
6	Tree volume (m^3)	12.01	7.65	14.89	0.34	15.51	1.75	8.34
7	Tree green biomass (kg)	80.72	55.75	102.12	0.85	33.45	3.54	11.83
8	Stand volume (Ha^{-3})	244.561	87.23	234.10	0.53	31.29	-0.257	-1.108
9	Stand green biomass (ton ha^{-1})	488.860	305.77	965.49	17.745	79.35	-512	-992
10	Stand dry biomass (ton ha^{-1})	325.423	188.29	409.98	12.865	56.54	-512	-992

Diameter Distribution Functions, Parameter Estimates and Assessment Criteria

The results in Table 2 showed the parameters for each of the diameter distribution functions associated to each diameter model screened for the forest reserve.

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Table 2: Summary of Parameters for the Selected Diameter Functions for Afi Reserve of Cross River State, Nigeria

Forest Reserve	Distribution	a	α_1	α_2	β	B	K	γ	δ	μ
Afi	Log-Logistic (3P)	1.68			9.48	9.76				
	Pearson 5 (3P)	1.93			18.54	7.50				
	Pearson 6 (4P)		17.99	1.94	1.01	7.97				
	Dagum (4P)	1.68			1.11	6.28	41.80			
	Frechet (3P)	1.70			10.42	6.06				
	Lognormal (3P)					9.52			1.01	2.29
	Gen. Pareto						0.27		10.74	11.07
	Inv. Gaussian (3P)					8.84		13.13		16.98
	Burr (4P)	97.94			40.90	-29.93	0.04			
	Gen. Extreme Value						0.41		6.97	17.01

Summary of Goodness of fit for Selecting Distribution Functions in Afi Forest Reserve, Cross River State, Nigeria

The results in Table 3showed the parameter estimates and assessment criteria of the diameter distribution functions in the study area. The goodness of fit was tested with Kolmogorov smirnov, Anderson Darling and Chi-Square. The Kolmogorov smirnov, Anderson Darling and Chi-Squared tests indicated that the ten distributions have good fits and therefore appropriate for diameter distribution assessment in the study area. However, D-values (Dagum4P: 0.0368, Burr 4P:0.04467, Gen. Extreme Value: 0.04716 and Log-Pearson 3P: 0.028, Pearson 5 (3P): 0.03426, Pearson 6 (4P):0.03465, and Frechet (3P):0.0373, Lognormal (3P): 0.04078, Gen. Pareto:0.04102 and Inv. Gaussian (3P):0.04366) were less than the tabulated value (0.05). The results further showed that Log-Logistic of three parameters (3P) was more flexible among the distribution functions and hence considered the best that can determine the distribution of diameter for the Reserve as shown in Table 3.

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Table 3: Goodness of fit for Selecting Distribution Functions in Afi Forest Reserve, Cross River State, Nigeria

Forest Reserves	Distribution	Kolmogorov Smirnov		Anderson Darling		Chi-Squared	
Afi River		Statistic	Rank	Statistic	Rank	Statistic	Rank
	Log-Logistic (3P)	0.028	1	1.2083	1	34.734	1
	Pearson 5 (3P)	0.03426	2	1.487	2	45.536	7
	Pearson 6 (4P)	0.03465	3	1.5091	3	44.926	5
	Dagum (4P)	0.0368	4	1.6583	4	47.621	8
	Frechet (3P)	0.0373	5	1.6651	5	47.695	9
	Lognormal (3P)	0.04078	6	1.7037	6	37.591	2
	Gen. Pareto	0.04102	7	154.02	44	N/A	
	Inv. Gaussian (3P)	0.04366	8	2.2281	7	39.363	3
	Burr (4P)	0.04467	9	2.9096	8	45.206	6
	Gen. Extreme Value	0.04716	10	4.3885	11	43.425	4

Validation of Diameter Distribution Models in Afi Forest Reserve

The performance of the selected diameter distribution model was also assessed to evaluate the distribution function that best predicts the diameter structure of the forest reserve. Table4 showed the validation results of diameter distribution models for the forest reserve.The paired T-test was used to validate the model by comparing the observed and predicted distribution. The model output of the models selected for the forest reserve recorded a non-significant difference (P>0.05) when compared with the observed values-Table 5.

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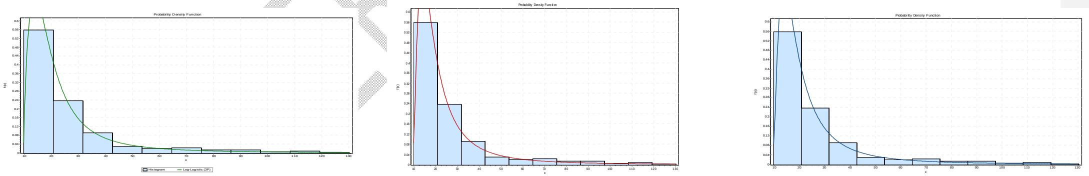
Also, Figures 1a, b and c showed the best three diameter distribution models based on the assess criteria for the forest reserve that can make appropriate fitting in diameter distribution. The best three models were Log-Logistic (3P), Pearson 5 (3P) and Pearson 6 (4P).

Table 4: Comparison of the Observed and Predicted Diameter for Log-Logistic (3P) Distribution Model

Dbh Class (cm)	Observed	Predicted
9.8 – 21.5	683.52	765.52
21.6 – 32.0	328.08	328.08
32.1 – 42.5	123.03	136.70
42.6 – 53.9	41.01	68.35
54.0 – 64.8	39.64	41.01
64.9 – 75.5	42.36	39.64
75.6 – 86.2	27.34	27.34
86.3 – 97.5	27.34	27.34
97.6 – 107.5	13.67	6.84
107.6 – 119.8	13.67	13.67
119.9 – 130.5	6.84	6.84

Table 5: T-Test Analysis for the selected Model in the Study Areas

Forest Reserves	Distribution	T-stat	T- crit	P-value	Remark
Afi River	Log-Logistic (3P)	0.11	2.09	0.91	Ns



Figures 1a, b and c: Best three Diameter Distribution Models for Afi River Forest Reserve

Discussion

Forest managers need to know every detail about the forest they are managing in terms of location, size, quantity and quality of the available resources in that forest estate. Information on how these resources are changing over time is also necessary for the sustainable management of the forest. This information can be obtained through proper resource modeling. In order to sustainably manage the forest, management goals must be formulated, effective treatment options capable of producing the desire results must be found and outcome of treatment in the productive system must be described and the required tool is diameter distribution (Nord-Larsen and Cao 2006).

Modeling the diameter distribution of a forest stand is an integral part of forest management and planning (Bassey and Adekunle, 2022). In this study, it was observed that there was a reduction in the number of stems per hectare as dbh class increases across reserve. The reductions in the number of stems per hectare as the dbh size class increased reflected the characteristics of a natural forest. This confirms the report of Adesuyi*et al.*, (2020) that trees in an uneven-aged forest grow continuously and have different reproductive periods. The continuous reproduction of new trees has been noted to bring about variation in ages especially in an undisturbed stand. Thus, diameter distribution in an uneven-aged stand is irregular. Bassey and Adekunle (2022) stressed that as the area of the stand increases, the irregularities tend to even out and the inverse J-shaped diameter distribution becomes apparent.

Comment [BB8]: Not necessarily. The structure of a natural forest is generally made up of trees of different sizes and ages. The increased predominance of young trees may therefore be a sign of disturbance caused by logging, for example.

High positive skewness and peakedness were also observed. This is an indication that considerable numbers of trees are concentrated in the lower diameter classes in each of the reserve (Gadow, 1983). The high positive skewness could also be attributed to the size of sample plot (50m x50m) and number of trees per plot(≥ 60).This finding agrees with the report made by Shiver (1988) who found that 50 trees per sample plots would be acceptable for most of the investigation works that try to capture the diameter distribution in Slash pine plantations. Nord-Larsen and Cao (2006) affirm that diameter distributions are affected by the spatial structure and the size of the plots. Nord-Larsen and Cao (2006) further emphasized that a better fit can be obtained with larger plots, but the number of plots should also be considered.

The high positive skewness could also mean good stand stock; by extension, it means even though there is continuous logging in the forest reserve, logging is still very low and management approach should be intensified in the management of the reserves in order to sustain the reserve especially it is among the few of the remaining rainforest reserves in Nigeria. This finding further agreed with the findings of Nurudeen, (2011) who reported high skewness and kurtosis as an indication of right tailed distribution and also the evidence of a good stock of a stand.

More so, the relatively low encroachment level in the reserve could partly be the reason for the higher aboveground biomass recorded than the values reported for tropical rainforest ecosystems in Nigeria by previous researches (example; Adekunle *et al.*, 2004 who reported 181.36 m^3/ha in Shasa Forest Reserve; 227 m^3/ha in Ala Forest Reserve; 91.71 m^3/ha in Omo Forest Reserve; and Adekunle and Olagoke, 2008 who reported 262.36 m^3/ha). The higher values obtained in this study is an indication forest reserve is probably one of the richest of the tropical rainforest left in Nigeria, as also reported by ITTO (2011).

Comment [BB9]: Don't forget that in the description of the study area, it is mentioned that the vegetation above 500 m has been transformed into grassland as a result of annual bush fires.

Conclusion

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Recommendations

1. The fitted models should be used by the Cross River State Forestry Commission for effective monitoring and better management practices of the reserve.
2. Comprehensive studies involving parameter prediction and parameter recovery methods taking information provided in this study as a foundational resource should be carried out across the study area.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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