Non-Linear Models for Tree Aboveground Biomass and Volume Estimation in Agoi-Ibami Forest Reserve, Cross River State, Nigeria

Abstract

Globally, allometric equations based tree biomass and volume estimation is a popular non-destructive method for estimating biomass, sequestered carbon and volume. This study fitted and validated non-linear models for individual tree biomass and volume in Agoi-Ibami Forest Reserve of Cross River State, Nigeria. Systematic line transects sampling method which involved the establishment of two parallel lines transects of 1500m in length with a distance of 500m between them was used for this study. Ten sample plots of 50m X 50m in size were laid in alternate along each transect at 100m interval. So, a total of 20 sample plots were enumerated. All tree species encountered in each sample plots were identified with their botanical names. In addition, tree growth variables such as dbh, height and diameters at the base, middle and top of every living tree in each plot with dbh >10cm were identified and measured for this study. Non-destructive method of biomass estimation was adopted. Diameter at breast height and total height were used to determine the aboveground green biomass for each tree. Conversion factors were applied to estimate stand biomass, carbon sink and sequestered carbon dioxide (CO_2) for the forest reserve. Non-linear models were fitted for volume and aboveground biomass estimation in the study area. All the models were assessed and validated using some assessment statistical criteria and residual graphs. Models with good fit were recommended for use. Curve Expert Software was used for the development of the non-linear regression models. The Agoi-Ibami Forest Reserve had a total value of 391N ha^{-1} for number of stem per hectare, 14 tree families, mean dbh of 26.04cm, height of 15.9m and basal area of 50.21m^2ha^{-1}. The volume, aboveground green biomass and dry biomass of 263.19m^3 ha^{-1}, 459.67t ha^{-1} and 333.25t ha^{-1} respectively were obtained. The Ratkowsky, Weibull, and Logistic models were the best non-linear volume and aboveground biomass models for the forest reserve based on the assessment criteria. Therefore fitted should be used for the efficient and effective management of the forest reserve.

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Keywords: Tree volume, Aboveground biomass, Dry biomass, Non-linear and Global warming

Introduction

The scientific community globally considers carbon dioxide (CO_2) as one of the critical contributors to climate change and ultimately, global warming. An excessive amount of atmospheric carbon is accelerating climate change through the greenhouse effects (Mahmood *et al.*, 2019a). The removal of this atmospheric carbon is one of the challenging and expensive tasks globally today. Trees can sequester atmospheric carbon in its biomass through photosynthesis and tree growth and this biological means of carbon removal is the only cost-effective path. Therefore, the estimation of biomass especially using allometric models as a non-destructive method is critically important in tree biomass determination. However, the allometric model development process follows both the destructive and semi- destructive methods (Chave *et al.,* 2014). Non-destructive biomass estimation method which is widely known as the allometric model method is followed for the estimation of tree biomass and sequestered carbon.

Biomass estimation is getting sufficient attention from the scientific communities as it bears significant importance from a carbon trading point of view. Globally, researchers are

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continuously trying to develop allometric models for estimating tree biomass non-destructively (Bassey and Ajayi, 2020). Site-specific and species-specific allometric equations inherit the precise results (Hossain *et al.,* 2020; Mahmood *et al.,* 2019b). Some researchers put concentration on the development of the species-specific model (Daba and Soromessa, 2019; Diédhiou *et al.,* 2017; Kebede and Soromessa, 2018); however, some researchers have interests to develop general allometric models applicable for different specific sites (Ounban *et al.,* 2016). Furthermore, most of the research works used linear regression equations with the combinations of different dendrological variables for both volume and biomass estimation (Hossain *et al.,* 2016; Hossain *et al.,* 2020; Hossain *et al.,* 2015; Mahmood *et al.,* 2019a; Mahmood *et al.,* 2019b). Moreover, applying direct destructive techniques for biomass estimation and develop allometric models are time-consuming, demand specialized labor and are very expensive (Bassey *et al.*, 2022). In most cases, such destructive studies are restricted to small trees for cost reasons and harvesting trees requires special authorization which is habitually difficult to acquire, and consequently only a few valid equations are available. Generic equations ignore key innate differences arising from species diversity and variation in species parameters such as local wood density as a main ecological trait. In addition, researchers argue that before allometric equations are used, their validity within a particular geographic location needs to be tested (Bassey *et al.*, 2022).

Conversely, the use of locally developed equations that permit the estimation of volume and total aboveground biomass of a specific tree species as a composite of biomass components such as trunks, large branches and small branches is in dare need. Allometric equations that estimate biomass based on locally measured tree variables such as height, diameter, wood density, and crown are more accurate than fitted equations. Advantages of such equations are explicit to species, sites, tree age and management and possess higher levels of accuracy and are preferred means of biomass estimation. The sustainable management of forest resources requires a large amount of supporting information especially when managing the forest for production of commercially valuable materials. Some tree variables, including volume are extremely time consuming to measure on field but can be predicted by using inventory data. However, in many cases, there are no models available for predicting volume components that are location specific and based on data covering the entire target area of forest inventory. Collecting data for developing volume models is very time consuming and expensive and requires a lot of precise measurements and sampling operations along a tree (Bassey *et al.*, 2022). This research estimated the stand biomass and volume and developed a set of non-linear equations for individual tree biomass and volume estimations.

METHODOLOGY

Study Area

The Agoi-Ibami Forest Reserve is situated in Yakurr Local Government Area of Central Cross River State, Nigeria. Yakurr Local Government Area is located approximately between Latitude 5°45’ and 5055’ north of the equator and Longitude 8°11’ and 8°20’ east of the Greenwich meridian and 120km2 (75 miles) North West of Calabar, the capital of Cross River State. Yakurr is located within the equatorial forest region of the tropics. The area is characterized by high temperature, rainfall and humidity (Okoi-Uyouyo, 2002).

Sampling Procedure and Data Collection

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Systematic line transect was employed 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 in the study. Sample plots of 50m x 50m in size were laid in alternate along each transect at 100m interval and thus summing up to 10 sample plots per 1500m transect and a total of 20 sample plots in the forest reserves. In each plot, all living trees with dbh ≥10cm were identified and measured. 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. 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 Bassey and Ajayi, (2020).

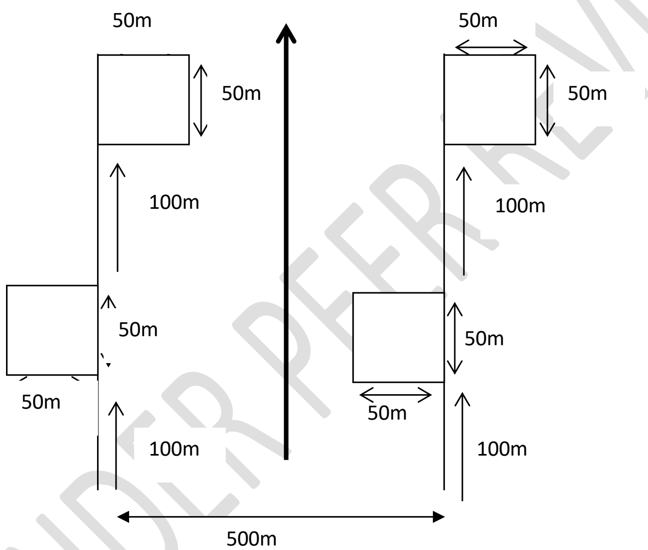

Figure 1: Plot layout with systematic line transects sampling technique

Tree Species Identification

All the tree species were identified with their botanical names and distributed into their respective families. The botanical name of every living tree encountered in each sample plot was recorded for each of the sample plot. However, when a tree's botanical name was not known, immediately, it was identified by its commercial name or local name. Such commercial or local name was translated to correct botanical names using.

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Data Analysis

Basal Area Estimation

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

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

Where: D = diameter at breast height (m)

$\pi = 3.142$

BA = Basal Area (m^2).

D = diameter at breast height (m)

The total 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:

$$\overline{BA_p} = \frac{\Sigma BA}{n}$$

Where:

$\overline{\mathrm{BA_p}}$ = Mean basal area per plot and

n = Total number all possible sample plot

Stem Volume Estimation

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

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$$V = \frac{H}{6}[A_b + 4A_m + A_t]$$

Where:

V= Volume (m^3)

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

A_m = Mid basal area (m^2)

A_t = Basal area at the top (m^2)

H = height (m)

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.

Mean volume for the sample plot was calculated thus:

$$\overline{V_p} = \frac{\Sigma V_p}{8}$$

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$$\overline{V_p} = \text{Mean plots volume}$$

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 (Adekunle, 2007).

Biomass and Carbon Stock Estimation

To estimate the aboveground live biomass, the equation of Brown (1997) for mixed species in the tropical wet climate zone was adopted. The equation is given as

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$$Y = 21.297 - 6.952(D) + 0.740(D^2)$$

Where; Y = biomass per tree in kg and D = diameter at breast height (dbh) in cm.

Below ground biomass was estimated as 15% of the aboveground biomass.

Estimation of Carbon-dioxide Equivalent from Carbon Stock

The content of carbon in woody biomass of any forest is generally 50% of the tree total volume. Hence, to compute the weight of carbon stock of a tree was obtained by multiplying the dry weight of the tree by 50% (Eneji *et al.*, 2014). Therefore, the equation for the measurement of carbon-dioxide equivalent is given as:

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$$\text{Carbon dioxide emission} = Sc\ X\ 3.67 \quad . \quad . \quad . \quad . \quad . \quad \text{eq. 9}$$

where,

Sc = sequestered carbon (Ajayi and Adie, 2019).

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Generation of Non - Linear Tree Volume and Aboveground Biomass Models

For the Non Linear Tree Volume and Aboveground Biomass Models, field inventory data were divided into two. The first set (calibrating set) which comprises of 70% of the data was used to generate the models while the second set which comprises of 30% of the data was used to validate the models. The two models were generated using Curve Expert Professional software. The non-linear regression models generated using the model functions presented in Tables 1 and 2 for tree volume and biomass respectively.

Table 1: Non Linear Tree Volume Models

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Model	Model Functions
Logistic Power	V = a/(1+(x/b)**c)
Gompertz Relation	V = a*exp(-exp(b-c*x)
MMF	V = (a*b + c*x^d)/(b + x^d)
Weibull	V = a - b*exp(-c*x^d)
Logistic	V = a/(1 + b*e^(-cx))
Ratkowsky model	V = a / (1+exp(b-c*x))

a, b, c and d are the regression parameter to be estimated, V is the volume (m^3) and x is the Dbh (cm) while exp. is the exponential.

Table 2: Non Linear Aboveground Biomass Models

Model	Model Functions
Logistic Power	Y = a/(1+(x/b)**c)
Gompertz Relation	Y = a*exp(-exp(b-c*x))
MMF	Y = (a*b + c*x^d)/(b + x^d)
Weibull	Y = a - b*exp(-c*x^d)
Logistic	Y = a/(1 + b*e^(-cx))
Ratkowsky model	V = a / (1+exp(b-c*x))

a, b, c and d are the regression parameter to be estimated, Y is the Biomass (t) and x is the Dbh (cm) while exp. is the exponential.

Criteria for Non-linear Volume and Biomass Model Selection
All the non-linear models were assessed with the Standard error of estimate (SEE) and Akaike Information Criterion AIC as thus:

i. Standard Error of Estimate (SEE):
It is the square root of the average squared error of prediction and it is used as a measure of the accuracy of prediction. SEE is expressed as:

$$SSE = \sqrt{\frac{\Sigma[y_i - \hat{y}_i]^2}{n-p}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{eq. 10}$$

where,

y_i = Actual tree volume
$\hat{y}_i$= Predicted treevolume
n = Number of observations
p = Number of parameters in the volume models.

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The value must be small to be judged a good model.

ii. Akaike's Information Criterion (AIC)

The idea of AIC (Akaike, 1973) is to select the model that minimizes the negative likelihood penalized by the number of parameters as specified in equation as thus:

$$AIC = 2Logp(L) + p \quad \text{. eq. 11}$$

Where,

L refers to the likelihood under the fitted model and

p is the number of parameters in the model.

Model validation

Residual graphs were used for the validation of the volume and biomass models selected in the study.

RESULTS

Summary of Growth Variables of the Study Area

Results is Table 3 revealed that a total of 1277 individual trees (dbh ≥5cm) were identified and measured for tree height, dbh, basal, mid and top diameters in each of the sampling plots with total number of stem per hectare of 319N ha^{-1}. The Reserve further recorded a mean dbh value of 26.04cm, mean total height of 15.9m, basal area of $50.21m^2ha^{-1}$ with a stand volume of $263.194M^3$ ha^{-1} with a stand aboveground green biomass ranged of 459.67t ha^{-1} and dry biomass value of 333.25t ha^{-1}.

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Table 3: Summary of Growth Variables of the Study Area

S/N	Parameters	Mean	Min.	Max.	Std. Error	Std. Deviation	Skewness	Kurtosis
1	No. of sample plots measured	20						
2	No of trees measured	1277						
3	Number of stem per hectare	391.54N ha^{-1}						
4	DBH(cm)	26.04	4.00	95.10	0.7883	26.03	3.11	19.21
5	Height (m)	15.9	12.21	40.15	0.55	19.14	2.72	9.32
6	Basal area. (m^2 ha^{-1})	50.21	35.01	43.20	0.88	30.21	2.53	12.24
7	Tree volume (m^3)	18.60	8.23	35.19	0.34	15.51	1.75	7.02
8	Tree green biomass (kg)	69.44	61.75	112.12	0.85	33.45	3.54	24.13
9	Stand volume (Ha^{-3})	263.19	90.20	108.12	0.53	73.51	2.41	9.33
10	Stand green biomass (ton ha^{-1})	459.67	310.22	410.19	17.745	79.35	-512	-705
11	Stand dry biomass (ton ha^{-1})	333.25	192.9	212.16	12.865	56.54	-512	-864

Non-Linear Volume Models and their Assessment Criteria

The non-linear models considered for screening were Logistics, Gompertz Relation and Logistic Power, Ratkowsky, Richards, MMF, and Weibull models. However, all the screened models were found to be good models in describing diameter-volume relationship of trees in the study area. Results in Table 4 showed that Ratkowsky model was the best followed by Logistic Power, Weibull and Gompertz Relation, MMF and Logistic in that order based on the assessment criteria of the models (lowest AIC and standard error values). Furthermore, Figure 1 revealed three best non-linear tree volume models for the Agoi-Ibami Forest Reserve; meanwhile Figure 2 showed the residual plots of the selected three best nonlinear volume models. It indicated an even spread of above and below the zero line with no systematic trend implying that the selected model is fit for tree volume estimations.

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Table 4: Non-Linear Volume Models and their Assessment Criteria in Agoi-Ibami Reserve

Forest Reserves	Models	Parameters Estimate				AIC	Std Error
		A	B	C	D		
Agoi-Ibami	Weibull	30.43	26.12	10.48	4.78	2847.67	3.06
	Logistic Power	28.11	33.57	5.82		2838.83	3.04
	MMF	-4.00	273.79	63.18	1.20	3214.80	3.53
	Gompertz Relation	31.44	3.12	0.10		2849.05	3.06
	Logistic	-4.37	-7.88	0.05		3393.10	3.79
	Ratkowsky	24.58	7.36	0.23		2826.71	3.03

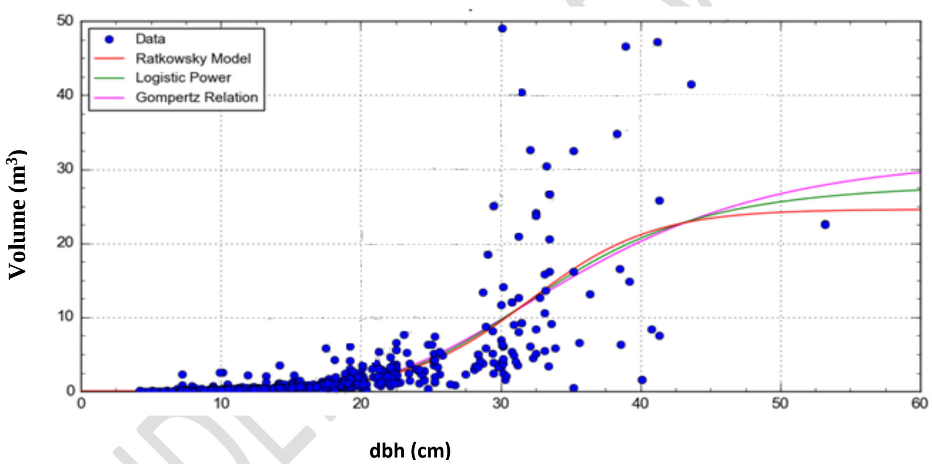

Figure 2: Best Three Non-Linear Volume Models in Agoi-Ibami Forest Reserve

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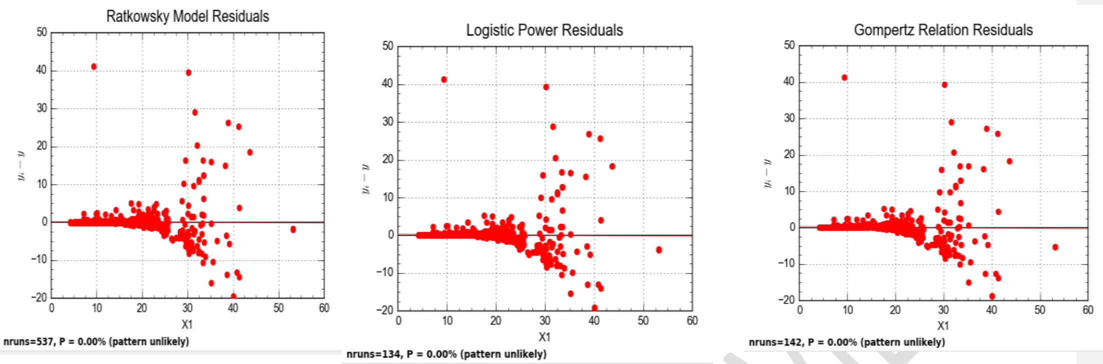

Figure 3: Residual Plots for Three Selected Non-linear Volume Models in the Study Area

Non-Linear Aboveground Tree Biomass Models and their Assessment Criteria

The non-linear aboveground tree biomass models considered for screening were Logistics, Gompertz Relation and Logistic Power, Ratkowsky, Richards, MMF, and Weibull models. The results in Table 5 showed the best models for non-linear models generated for the aboveground biomass estimation in the study arae. Importantly, recommendations of the best model(s) were based on the model assessment criteria (lowest AIC and standard error values). Ratkowsky model ranked best followed by Logistic Power and Logistic models. MMF and Weibull models ranked 4th and ranked 5th respectively. Figure 4 showed the best non-linear tree aboveground biomass model for the reserve. Also, Figure 5 presented the residual plots for the selected three nonlinear aboveground biomass models. It indicates an even spread of above and below the zero line with no systematic trend implying that the selected model is fit for tree biomass estimations.

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Table 5: Non-Linear Aboveground Biomass Models and their Assessment Criteria

Forest Reserves	Models	Parameters Estimate				AIC	Std Error
		A	B	C	D		
Agoi-Ibami	Weibull	21.27	-96.28	109.96	105.66	2918.10	3.16
	Logistic Power	21.52	169.51	0.25		2915.96	3.16
	MMF Gompertz Relation	20.99	11.02	28.02	-0.25	2917.97	3.16
	Logistic	21.23	1.97	1.08		2916.08	3.16
	Ratkowsky	21.61	2480.54	361.58		2437.98	3.04

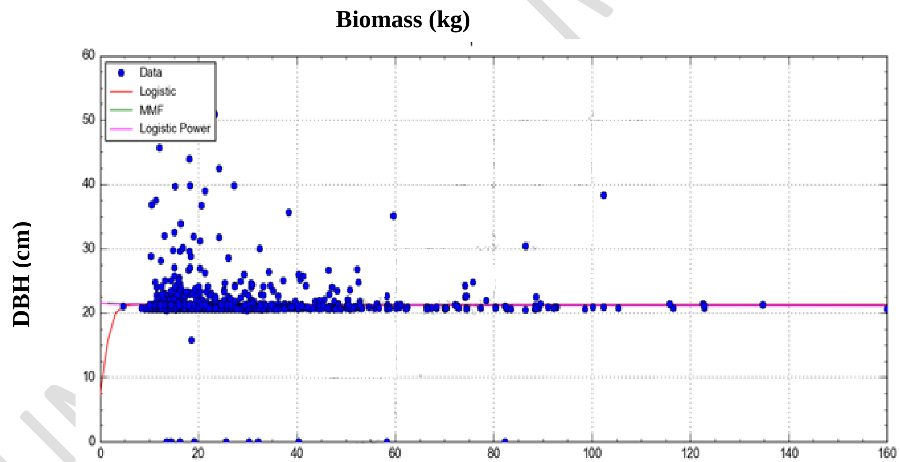

Figure 4: Three Selected Non-Linear Aboveground Biomass Models in the Study Area

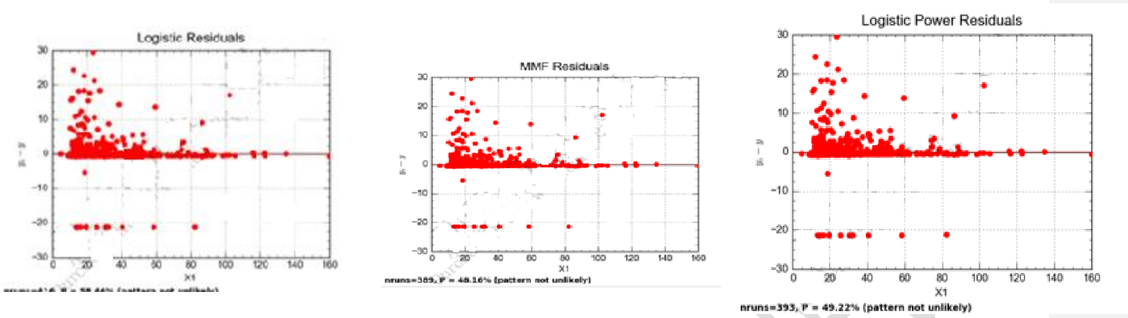

Figure 5: Residual graphs for the Three Selected Non-Linear Biomass Model in the Study Area

Discussion

The study fitted and validated the adequacy of nonlinear models for tree volume and aboveground biomass estimation in the Agoi-Ibami Forest Reserve of Cross River State. Logistic Power, Logistic, Ratkowsky, MMF, Gompertz Relation, and Weibull models were considered suitable for describing the volume and tree diameter relationship and biomass and tree diameter in the study area. This agrees with the findings made by Adesuyi *et al.*, (2020) that Logistic Power, Logistic, Gompertz Relation, Ratkowsky, MMF, and Weibull models were suitable for describing the volume-diameter relationship in strict nature reserve, South-West, Nigeria. However, Ratkowsky was the most flexible and consistent model in the reserve for tree volume and diameter relationship. This further revalidated the claims earlier made by previous authors (Nelson *et al.*, 2020). Therefore, the non-linear models generated and validated for both volume and biomass can fitly be used for tree volume and aboveground biomass estimations in the study area.

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Conclusion and Recommendations

The sustainable management of forest resources requires a large amount of supporting information especially when managing the forest for production of commercially valuable materials. Determination of current tree growth variables which are not possible to measure easily, are also essential. The tropical rainforest is one of the major vegetation types of the globe and the effectiveness of sustainably managing a reserve depends greatly on the formulation of accurate and up-to-date and location specific models. This research therefore fitted and validated the adequacy of nonlinear models for tree volume and aboveground estimation in Agoi-Ibami Forest Reserve of Cross River State. Logistic model was the most appropriate for the estimation of tree volume and Ratkowsky model was the most consistent and flexible model for aboveground tree biomass estimation in the Study Area.

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Based on the findings of this study, the following recommendation is made:

1. Permanent sample plots should be established by the Cross River Forestry Commission in the study area to enhance and promote accurate data collection, and the development of models for informed management decisions.

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