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

Abstract

Tree biomass and volume estimation based on allometric equations is a widely used non-destructive technique for estimating biomass, sequestered carbon, and volume worldwide. Non-linear models for the biomass and volume of individual trees in Nigeria's Cross River State's Agoi-Ibami Forest Reserve were fitted and validated in this study. In this study, two parallel lines transect of 1500 meters in length, separated by 500 meters, were established using the systematic line transects sampling method. Along each transect, ten sample plots, each measuring 50 m by 50 m, were placed alternately at 100 m intervals. Twenty sample plots in all were thus marked for the study. The estimation of biomass using a non-destructive method was used. To calculate the aboveground green biomass for each, the diameter at breast height and total height were employed. 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 50.21m2ha-1. Conversion factors were used to estimate stand biomass, carbon sink, and sequestered carbon dioxide (CO2). Non-linear models were fitted for volume and aboveground biomass estimation in the study area. All of the models were evaluated and validated using some assessment statistical criteria and residual graphs, and models with good fit were suggested for use. Curve Expert Software was used for the development of the non-linear regression models. According to the assessment criteria, the forest reserve's best non-linear volume and aboveground biomass models were the Ratkowsky, Weibull, and Logistic models. Fitted models should therefore be employed for the forest reserve's efficient and successful management.

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

Introduction

Globally, scientists believe that carbon dioxide (CO2) is one of the main causes of climate change and, eventually, global warming. Through the greenhouse effects, an excess of atmospheric carbon is hastening climate change (Mahmood et al., 2019a). Today, removing this carbon from the atmosphere is one of the most difficult and costly tasks in the world. Through photosynthesis and tree growth, trees may store atmospheric carbon in their biomass, making this biological method of carbon removal the only one that is economical. Therefore, it is crucial to estimate biomass, particularly utilizing allometric models as a non-destructive method, when determining the biomass of trees. But the process of developing an allometric model uses both destructive and semi-destructive approaches (Chave et al., 2014). Tree biomass and stored carbon are estimated using the non-destructive biomass estimation technique, commonly referred to as the allometric model method.

The scientific community is giving biomass estimation enough attention since, from the perspective of carbon trading, it is very important. Researchers throughout the world are always working to create non-destructive allometric methods for assessing tree biomass (Bassey and

Ajayi, 2020). The exact outcomes are passed down to species-specific and site-specific allometric equations (Hossain *et al.,* 2020; Mahmood *et al.,* 2019b). While some researchers focus on creating species-specific models (Daba and Soromessa, 2019; Diédhiou et al., 2017; Kebede and Soromessa, 2018), others are interested in creating general allometric models that can be used at various targeted locations (Ounban et al., 2016).

Furthermore, majority of the study works employed linear regression equations with the combinations of several dendrological factors 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, employing direct destructive approaches for biomass measurement and construct allometric models are time-consuming, need expert personnel and are very expensive (Bassey *et al.,* 2022). Because of financial constraints and the fact that tree harvesting necessitates specific authorization, which is typically hard to obtain, such destructive research are typically limited to tiny trees. As a result, there are only a few reliable equations available. Key intrinsic differences resulting from species diversity and variation in species factors, such as local wood density as a primary ecological attribute, are ignored by generic equations. Furthermore, scholars contend that the validity of allometric equations within a certain geographic area must be examined before to their application (Bassey *et al.*, 2022).

On the other hand, there is a need for locally created equations that allow the volume and total aboveground biomass of a particular tree species to be estimated as a composite of biomass components such trunks, major branches, and small branches. Compared to fitted models, allometric equations that use locally measured tree factors like height, diameter, wood density, and crown to estimate biomass are more accurate. These equations have the advantages of being explicit to species, sites, tree age, and management; they are also more accurate and are the method of choice for estimating biomass. Particularly when managing the forest for the production of commercially important commodities, a substantial amount of supporting data is necessary for the sustainable management of forest resources. Certain tree factors, such as volume, can be predicted using inventory data but are very time-consuming to measure in the field. Nevertheless, there are frequently no models available for location-specific volume component predictions that are based on data including the whole target region of forest inventory. It takes a lot of time and money to gather data for volume model development, and it involves numerous accurate measurements and sampling procedures along a tree (Bassey *et al.*, 2022). In addition to estimating the biomass and volume of the stand, this study created a set of non-linear equations for estimating the biomass and volume of individual trees.

METHODOLOGY

Study Area

In Nigeria's Central Cross River State, the Agoi-Ibami Forest Reserve is located in the Yakurr Local Government Area. Approximately 120 km2 (75 miles) north-west of Calabar, the capital of Cross River State, and between latitudes 5°45' and 5055' north of the equator and longitudes 8°11' and 8°20' east of the Greenwich meridian is where you'll find it. The tropical zone of equatorial forests is where Yakurr is situated. High humidity, rainfall, and temperatures are characteristics of the region (Okoi-Uyouyo, 2002).

Sampling Procedure and Data Collection

Sample plots were set using a methodical line transect. The study employed two transects, each measuring 1500 meters in length and separated by at least 500 meters. A total of ten sample plots per 1500m transect, or 20 sample plots in the forest reserves, were spread out in alternating 50m × 50m plots spaced 100m apart throughout each transect. Every living tree in each plot that had a dbh of at least 10 cm was located and measured. Single tree DBH, other diameters (base, middle, and top diameters), and tree height were measured using a Spiegel relascope. The uphill side of trees growing on a slope was used to estimate the dbh. They regarded buttresses as non-commercial. Accordingly, the equivalent of dbh was measured 20 cm beyond the upper limit of the buttresses when they extended higher than 1.30 m above the ground. According to Bassey and Ajayi's (2020) recommendation, a more representative dbh point was selected either above or below the breast-height point when knots or localized deformations occurred-see figure 1.

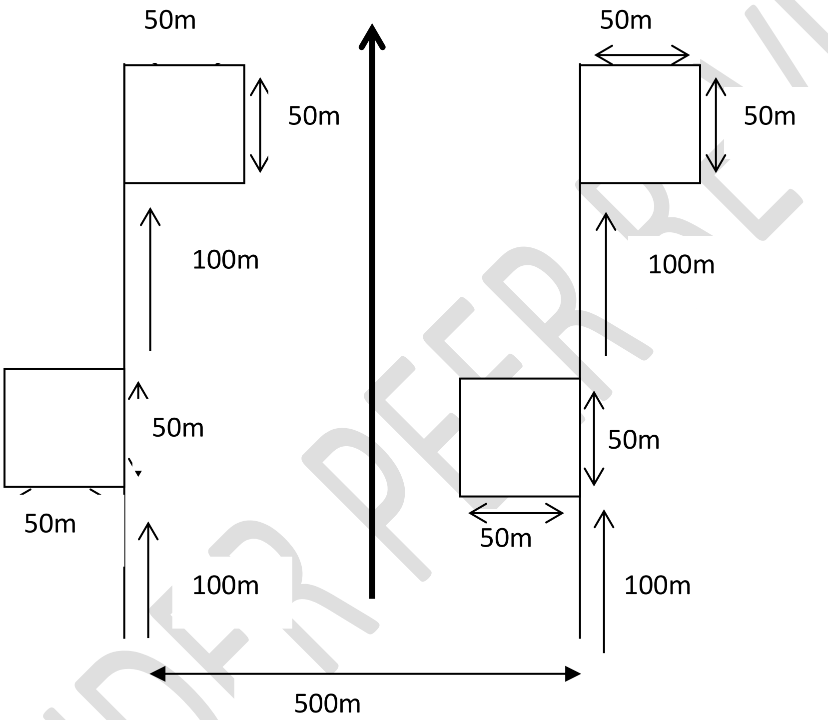


Figure 1: Plot Design Using a Methodical Sampling Methodology for Line Transects

Identification of Tree Species

Each species of tree was identified using its scientific name and categorized into its family (Keay, 1989). Every surviving tree found in each sample area was identified by its botanical name. On the other hand, trees were quickly identified by their local or commercial names when their botanical names were unknown. Using Keay (1989), such local or commercial names were converted to their proper botanical names.

Data Analysis

Basal Area Estimation

The basal area was calculated using the diameter at breast height.

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

where D is the breast height (m) diameter.

BA = Basal Area (m2) = π = 3.142.

D = diameter at breast height (m)

Each plot's mean basal area was determined using the following formula, while the total basal area (BA) was determined by summing the basal areas of all the trees in the plot:

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

Where:

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

$\mathrm{n} = \text{Total number all possible sample plot}$

Estimation of Tree Stem Volume

Using the Newton's formula developed by Husch et al. (2003), Adekunle (2007), and Bassey and Adekunle (2022), the volume of each individual tree was determined.

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

where V is equal to volume (m3)Ab is the base's area (m2).

Am stands for mid-basal area (m2).

At = The top's basal area (m2)

H is equal to height (m).

The mean plot volume was calculated by dividing the total plot volume by the number of sample plots, and the plot volumes were calculated by adding the volumes of each tree in the plot.

The sample plot's mean volume was determined as follows:

$\overline{V_p} = \frac{\Sigma V_p}{8}$ eq. 4

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

The mean per plot was then multiplied by the number of sampling units in a hectare to estimate the volume of trees per hectare (M^3ha) (Adekunle, 2007).

Estimation of Biomass and Carbon Stock in Agoi-Forest Reserve

The Brown (1997) equation for mixed species in the tropical wet climate zone was used to calculate the aboveground live biomass. The formula is provided as

$$Y = 21.297 - 6.952(D) + 0.740(D^2) \qquad \text{eq. 5}$$

where D is the diameter at breast height (dbh) in centimeters and Y is the biomass per tree in kilograms.

15% of the aboveground biomass was predicted to be belowground biomass.

Carbon-dioxide Equivalent Estimation

Typically, 50% of the total volume of trees in a forest's woody biomass contains carbon. Therefore, a tree's carbon stock weight was calculated by multiplying its dry weight by 50% (Eneji et al., 2014). As a result, the following is the equation for measuring carbon dioxide equivalent:

$$\text{Carbon dioxide emission} = Sc\ X\ 3.67 \quad . \quad . \quad . \quad . \quad . \qquad \text{eq. 6}$$

where,

Sc = sequestered carbon (Ajayi and Adie, 2018).

Tree Volume and Aboveground Biomass Non - Linear Models Formulation

Field inventory data were split into two categories for the Non Linear Tree Volume and Aboveground Biomass Models. Models were created using the first set (calibrating set), which included 70% of the data, and validated using the second set, which included 30% of the data. Curve Expert Professional was used to create the two models. The model functions shown in Tables 1 and 2 for tree volume and biomass, respectively, were used to create the non-linear regression models.

Table 1: Nonlinear Volume Models for Trees

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))

V is the volume (m3), x is the Dbh (cm), exp. is the exponential, and a, b, c, and d are the regression parameters to be calculated.

Table 2: Models of Nonlinear Aboveground Biomass

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))

Y is the biomass (t), x is the Dbh (cm), and exp. is the exponential. The regression parameters to be estimated are a, b, c, and d.

Selection Criteria for Non-linear Biomass and Volume Models

The Standard Error of Estimate (SEE) and Akaike Information Criterion (AIC) were used to evaluate each non-linear model as follows:

i. **Standard Error of Estimate (SEE):**

It serves as a gauge for prediction accuracy and is calculated as the square root of the average squared error of prediction. The expression for SEE is:

$$SSE = \sqrt{\frac{\Sigma[y_i - \hat{y}_i]^2}{n-p}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad \text{eq. 7}$$

where,

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

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

ii. Akaike’s Information Criterion (AIC)

Selecting the model that minimizes the negative likelihood penalized by the number of parameters as given in the equation as follows is the rationale behind AIC (Akaike, 1973):

$$AIC = 2Logp(L) + p \qquad \text{eq. 8}$$

Where,

L refers to the likelihood under the fitted model and

p is the number of parameters in the model.

Validation of Models

The volume and biomass models chosen for the investigation were validated using residual graphs.

RESULTS

Growth Variables of the Study Area

Findings are Tree height, dbh, basal, mid, and top diameters were measured for 1277 individual trees (dbh ≥5 cm) in each of the sampling plots, with a total number of stems per hectare of 319N ha-1, according to Table 3. A mean dbh value of 26.04 cm, a mean total height of 15.9 m, a basal area of 50.21 m2ha-1, a stand volume of 263.194 M3 ha-1, a stand aboveground green biomass range of 459.67 t ha-1, and a dry biomass value of 333.25 t ha-1 were also documented by the Reserve.

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

Criteria for Evaluating Non-Linear Volume Models

Logistics, Gompertz Relation and Logistic Power, Ratkowsky, Richards, MMF, and Weibull models were among the non-linear models taken into consideration for screening. The diameter-volume connection of the trees in the research region was well described by all of the screened models, nevertheless. Based on the models' evaluation criteria (lowest AIC and standard error values), the results in Table 4 indicated that the Ratkowsky model was the best, followed by Logistic Power, Weibull and Gompertz Relation, MMF, and Logistic in that order. Additionally, the top three nonlinear tree volume models for the Agoi-Ibami Forest Reserve were identified in Figure 1, and the residual plots of these three models were displayed in Figure 2. It showed a uniform distribution above and below the zero line with no discernible pattern, suggesting that the chosen model is appropriate for estimating tree volumes.

Table 4: Evaluation Standards for Non-Linear Volume Models 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

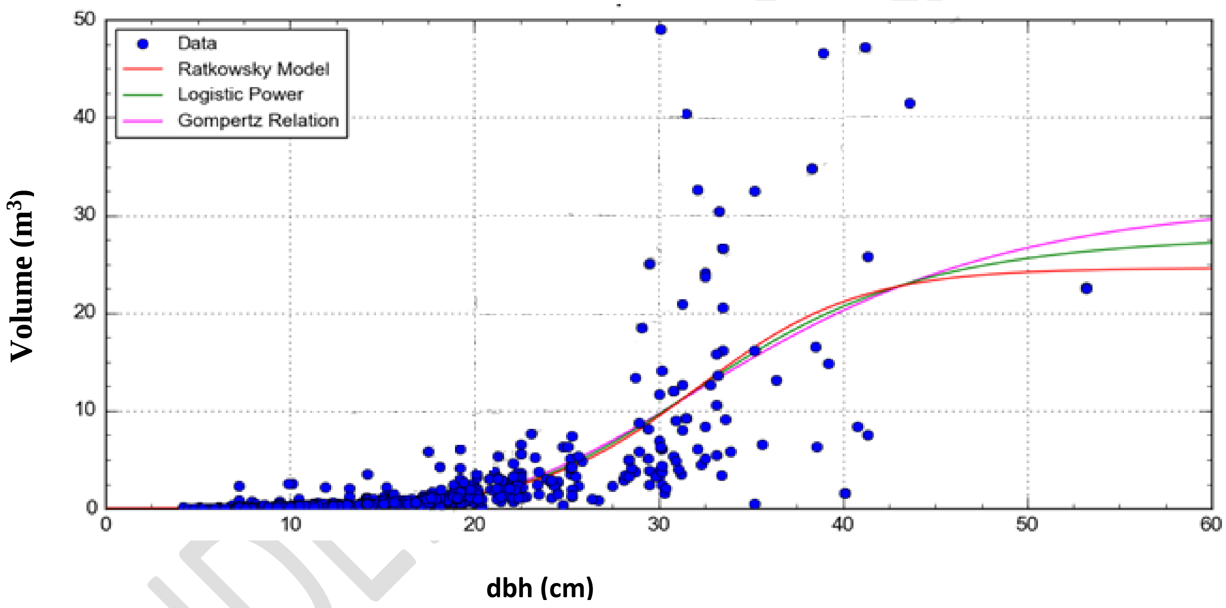
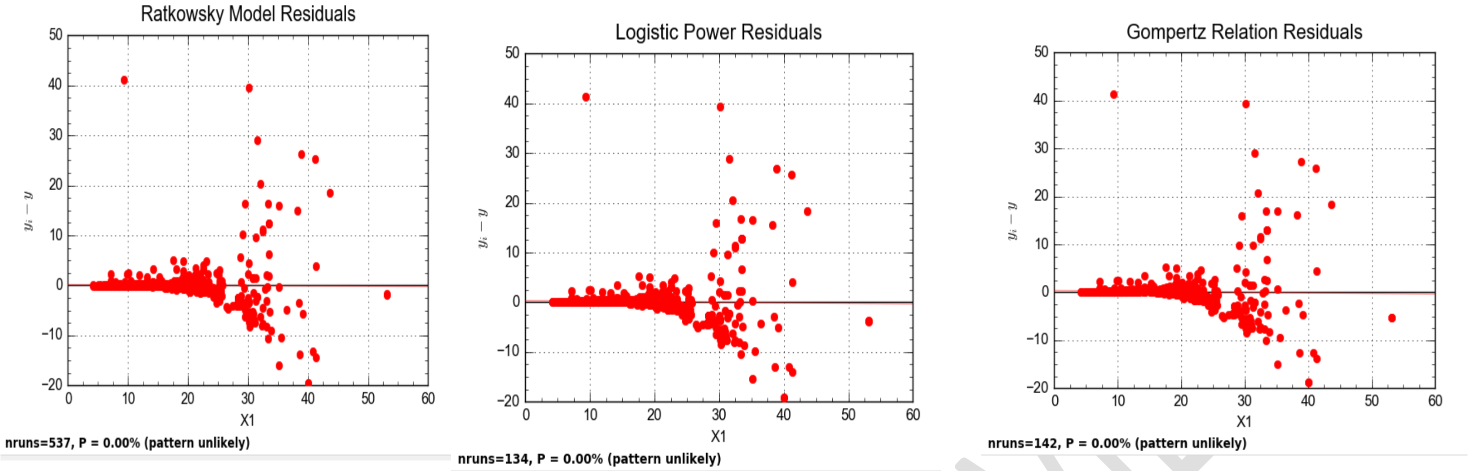


Figure 2: Agoi-Ibami Forest Reserve's Top Three Non-Linear Volume Indicators



nruns=537, P = 0.00% (pattern unlikely)

nruns=134, P = 0.00% (pattern unlikely)

nruns=142, P = 0.00% (pattern unlikely)

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

Non-Linear Aboveground Tree Biomass Models and their Assessment Criteria

Ratkowsky, Richards, MMF, Weibull, Logistics, Gompertz Relation, and Logistic Power were the non-linear aboveground tree biomass models that were taken into consideration for screening. The best non-linear models produced for the study's aboveground biomass estimation were displayed in Table 5. Crucially, the model evaluation criteria (lowest AIC and standard error values) served as the foundation for the suggestions of the best model or models. Logistic models and Logistic Power came in second and third, respectively, to the Ratkowsky model. Weibull and MMF models came in fourth and fifth, respectively. The reserve's optimal non-linear tree aboveground biomass model was displayed in Figure 4. Additionally, the residual plots for the three nonlinear aboveground biomass models that were chosen were shown in Figure 5. It suggests that the chosen model is appropriate for estimating tree biomass since it shows an even distribution above and below the zero line without any discernible trend (Adesuyi, 2020; Bassey *et al.*, 2022).

Table 5: Assessing Non-Linear Aboveground Biomass Models and Their Requirements

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

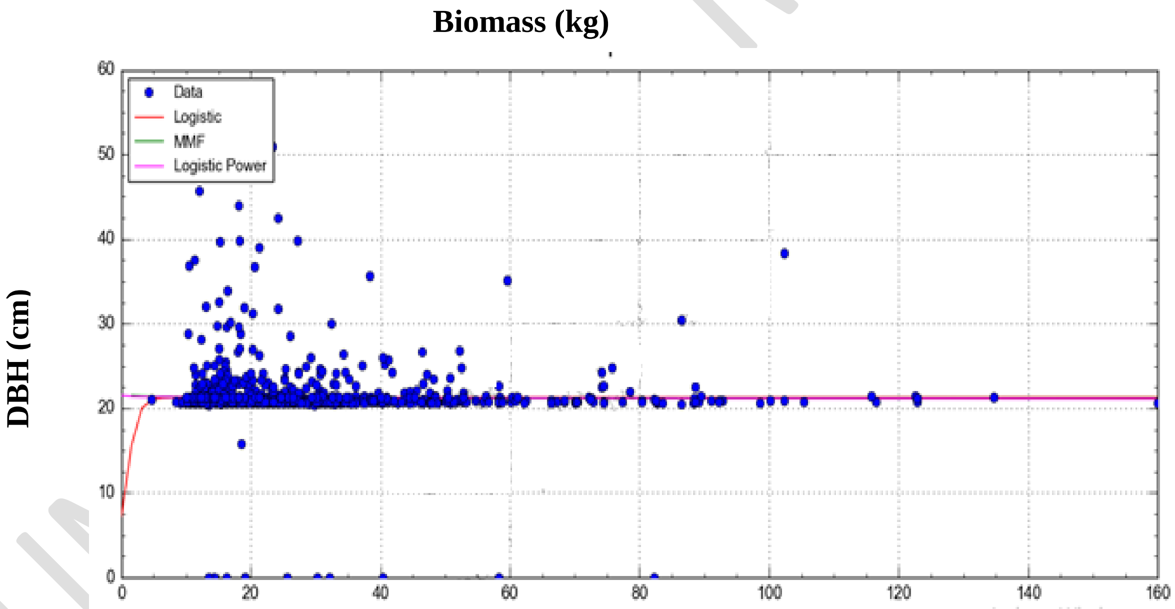


Figure 4: Three Selected Non-Linear Aboveground Biomass Models in the Study Area

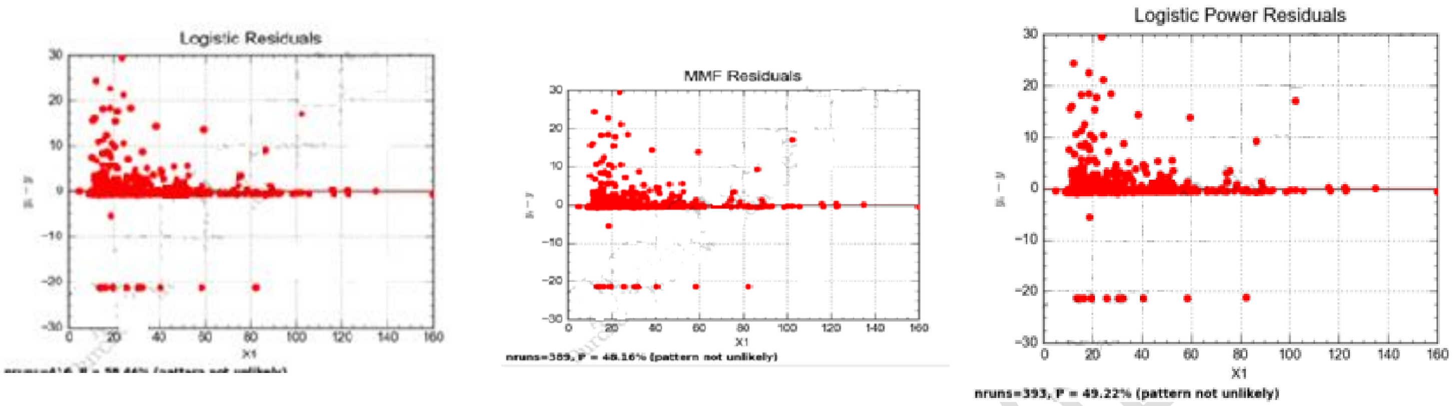


Figure 5: Three Selected Non-Linear Biomass Model Residual Graphs in the Study Area

Discussion

In the Agoi-Ibami Forest Reserve of Cross River State, the study fitted and verified the suitability of nonlinear models for estimating tree volume and aboveground biomass. The volume and tree diameter relationship, as well as the biomass and tree diameter relationship, in the research area were thought to be adequately described by the Logistic Power, Logistic, Ratkowsky, MMF, Gompertz Relation, and Weibull models. This supports the findings of Adesuyi et al. (2020), who found that the volume-diameter relationship in strict nature reserves in South-West Nigeria could be adequately described by the Logistic Power, Logistic, Gompertz Relation, Ratkowsky, MMF, and Weibull models. Ratkowsky, however, was the reserve's most adaptable and reliable model for the link between tree volume and diameter. This result is similar with Bassey et al.'s (2022) report, which found that the Ratkowsky model described volume and aboveground biomass in the Afi Forest Reserve in Cross River State, Nigeria, more consistently. This further supported the assertions previously made by other authors (Nelson et al., 2020). Thus, tree volume and aboveground biomass estimations in the research region can be appropriately done using the non-linear models that were developed and verified for both volume and biomass.

Conclusion and Recommendation

A substantial amount of supporting data is necessary for the sustainable management of forest resources, particularly when the forest is being managed for the production of commodities of economic value. It is also crucial to identify the current tree growth characteristics that are difficult to assess. One of the main vegetation types in the world is the tropical rainforest, and the development of precise, current, and site-specific models is crucial to the success of maintaining a reserve sustainably. Thus, in the Agoi-Ibami Forest Reserve of Cross River State, this study fitted and verified the suitability of nonlinear models for tree volume and aboveground estimation. The Ratkowsky model was the most reliable and adaptable approach for estimating aboveground tree biomass in the Study Area, whereas the logistic model was best suited for estimating tree volume. The non-linear models created for this research will be used to manage the reserve effectively and efficiently. Carbon monitoring and carbon trading in the reserve and other comparable forests within Cross River State's tropical rainforest zone will be based on the anticipated stand level biomass.

The study's conclusions lead to the following recommendation:

The Cross River Forestry Commission should create permanent sample plots in the research area to improve and encourage precise data collecting and the creation of models for well-informed management choices.

Disclaimer (Artificial intelligence)

We hereby state that no generative AI tools, including text-to-image generators and large language models (ChatGPT, COPILOT, etc.), were used in the development or editing of this paper.

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