Interdisciplinary Journal of Agriculture and Environmental Sciences
ISSN: 2837-9977| Impact Factor: 8.17
Volume. 12, Number 3; July-September, 2025;
Published By: Scientific and Academic Development Institute (SADI)
8933 Willis Ave Los Angeles, California
https://sadijournals.org/index.php/IJAES|editorial@sadijournals.org

GROUND BIOMASS AND CARBON SEQUESTRATION OF SELECTED SACRED GROVES IN EDO STATE, NIGERIA

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DOI: https://doi.org/10.5281/zenodo.17092883

Abstract: Sacred groves are traditionally protected forest fragments that, play a vital role in biodiversity conservation and ecosystem service provision, including carbon sequestration. Despite their ecological significance, the aboveground biomass (AGB) and carbon storage potential of sacred groves in Nigeria remain underexplored. This study assesses the AGB and carbon sequestration capacities of selected sacred groves in Edo State, Nigeria, to highlight their contributions to climate change mitigation. A total of four sample plots measuring 30m × 30m were temporarily laid from which tree parameters where measured and estimated, DBH and total tree height were used as predictor variables for the aboveground biomass estimation. Three allometric models were used to estimate the aboveground biomass from which carbon sequestration was computed. The evaluation criteria of a high R^2 and a corresponding low value of RMSE, AIC, and BIC revealed that the allometric models were useful in estimating OGground biomass. The total number of CO_2 sequestered by the sacred groves was 2,894.18kg/ha, revealing the significant importance of sacred groves to the global world as compared to forest reserves, which are now only shadows of themselves.

Keywords: sacred-groves, carbon-stock, Milicia excelsa, biomass.

Introduction

Sacred groves are forest patches or areas that are protected by local dwellers. “It is a term used to refer to land or bodies of water that have special spiritual significance to peoples and communities (Verschuuren et al., 2010)”. Sacred groves, which hold strong cultural and religious importance to local people are increasingly recognised as a traditional form of community-based conservation (Bulkan, 2017; Ormsby and Bhagwat, 2010). The majority are small in size, generally close to houses (Agbo and Sokpon, 1997), and have a spiritual value specific to the communities.

Biomass refers to the total amount of energy stored in the trees for the next tropic level. The total dry weight of all living organic matter found above ground in an ecosystem of trees or forests is referred to as AGB. The tree biomass from forest ecosystems plays a key role in the sustainable management of natural resources and in the contribution of forests to the global carbon cycle (Brown 2002; Zianis, Mencuccini 2003). It is essential to accurately estimate AGB to monitor the production and health of forests. (Egonmwan and Samuel, 2025).

Carbon sequestration is the natural process of absorbing CO_2 from the atmosphere and storing it in diverse pools, such as oceans, forest ecosystems, and soil organic matter (SOM) (Kirschbaum, 2003; Sundquist et al., 2008). Carbon stock refers to the amount of carbon that is accumulated and stored in different forest species. The biomass expansion factor (BEF), which fixes the ratio between the volume of the forest and its biomass, is believed to be a fairly reliable method of assessing carbon stock (Sun & Liu 2019). The remote sensing technologies used to evaluate carbon sequestration potentials include LiDAR, aerial surveys, and satellite imagery (Dossa and Miassi 2024).

Over the past 50 years, atmospheric carbon dioxide levels have risen at an alarming rate, mostly because of human development. Human population growth has had a significant effect on the global carbon cycle, which is normal. Ravindranath et al. (1997) and Chavan and Rasal (2012) stress that the rise in carbon emissions is a severe global problem for the whole world. Fortunately, nature provides ways to absorb carbon from the air. Oceans, forests, and soils are the main ones that do this.

The majority of the studies that have developed allometric equations for Nigerian forests have been conducted on public forests such as the Oluwa forest reserve (Onyekwelu, 2014) and the, Kpashimi forest reserve (Jibrin and Abdulkadir, 2015). These models are often specifically developed for plantation tree species with high economic values, such as Tectona grandis (Ojo et al., 2020), Gmelina arborea (Onyekwelu, 2014), and Khaya senegalensis (Aghimien et al., 2020). However, only a few studies (e.g., Jibrin and Abdulkadir, 2015) have developed models for high abundance indigenous tree species in secondary forests, which are of considerable importance to local livelihoods. Similarly, little or no consideration has been given to the carbon sequestration potential of sacred groves forest ecosystems. With this knowledge gap, is necessary to know how much carbon is stored in ecosystems such as sacred groves to determine how much carbon flows from ecosystems to the atmosphere and back. Hence, this study aimed to estimate the biomass and total carbon sequestered in the two selected sacred groves, with a focus on climate mitigation and the importance of protecting the groves and other natural plants found therein.

Materials and Methods

Methodology

Study Area

The study was conducted in the southern and central parts of the state of Edo. Edo State is situated between latitudes 5º 5′N - 7º 35′N and longitudes 5ºE - 6º 40′E, (Wright, et al. 1985) of the Greenwich Meridian. It has a total land area of approximately 2,301 km^2. Rock deposits formed during the Cretaceous and Tertiary periods characterize the geology of Edo State. The area experiences high levels of sunlight throughout the year, with some reports indicating over 1600 h of sunshine annually. Sunshine levels vary depending on the season. The natural vegetation in this area is typically similar to that of tropical lowland rainforest. However, due to human activity over a long period, the original forest has been replaced by a secondary forest, which has regrown after significant disturbance (Egonmwan and Samuel, 2025).

Two sacred groves were purposively selected for this study based on accessibility. The Ekosodin sacred grove is located within two local government areas, namely, as Egor and Ovia North-East local government areas, Benin City Edo state, Nigeria (Mitanna, 2021), with a coordinate of latitudes 6° 23' 53.16" N - 6° 23' 53.16" N and longitudes 5° 36' 54.36" E - 5° 37' 51.96" E. The Oza Nisi sacred grove is located within the Orhionmwon local government area, with latitudes of 6° 20' 26" N - 6° 20' 33" N and longitudes of 6° 03' 05" E - 6° 03' 08" E. The occupation of the local dwellers is farming and they "revere" the sacred grove and view trespassers as incurring the wrath of the "gods" or "ancestors".

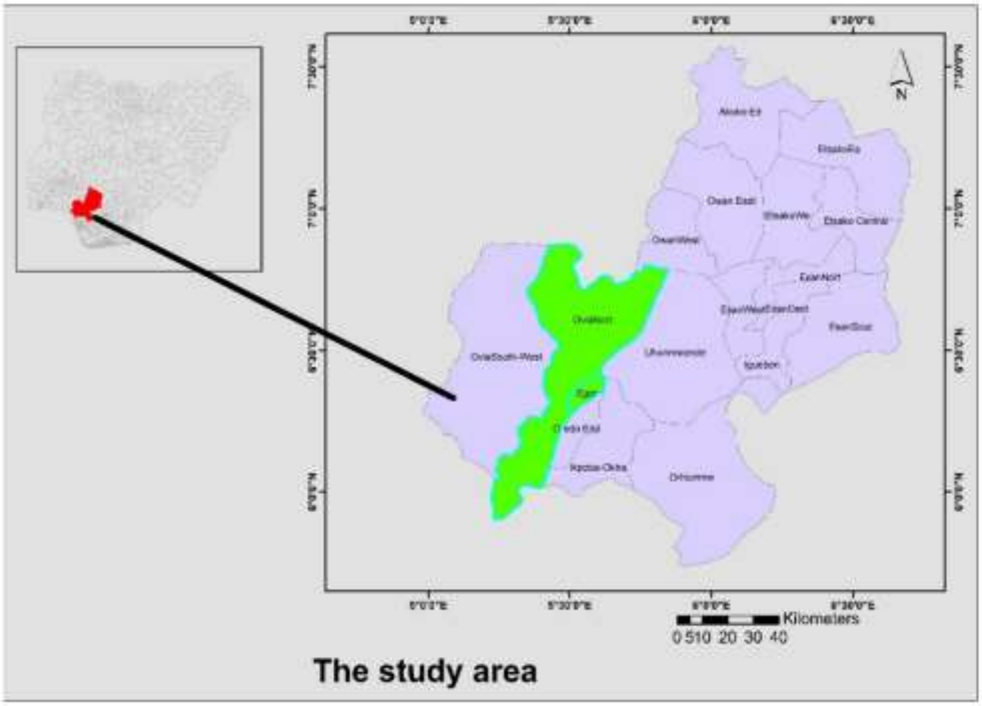

Fig.1. The study area

Data Collection

Two TSPs measuring 30 m × 30 m were laid in each sacred grove, totaling four from which tree variables were measured across the study area. Four temporary sample plots in the sacred groves. Tree variables measured within the sample plots were diameter at the base, midpoint, top and breast height, denoted as Db, Dmid, Dt and Dbh all in centimeters, respectively. Using a stick 1.3m from the ground placed at every identified by a taxonomist with tree of < 10cm excluded from the study, Db and diameter at breast height were measured using a measuring tape, while total height (H) and all other diameter parameters were measured using Spiegel relaskop. Next, the specific wood densities of the trees were manually obtained from the Global Wood Density (GWD) database. Owing to the small size of sacred groves, plot dimension as small as 10 m × 10 m can be used.

Volume will be computed using Newton's formula, which represented as follows:

$$V = \frac{\pi H\left(D_b^2 + 4D_m^2 + D_t^2\right)}{24} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where: V = Observed volume outside bark in cubic metres (m^3), π = Pi given as 3.142, Db, Dm, and Dt (m) = Diameters measurement at base, mid-point and top, respectively and H(m) = Total tree height

The volume computed will be converted to biomass by the wood density and an expansion factor following Pajtik et al. (2011). The wood density of 0.69 was obtained from the World Wood Density Database for tropical trees. The aboveground tree biomass was estimated using the following equations:

$$B = V * WD * BEF \qquad \ldots\ldots\ldots\ldots\ldots \qquad (2)$$

B: Biomass which is the aboveground tree biomass (kg); BEF: biomass expansion factor; WD: wood density ($kg.m^{-3}$). The biomass expansion factor can be obtained as the ratio of the aboveground biomass (B) to the standing tree's wood volume (Vss). A biomass expansion factor (BEF) of 1.69 was used (Hossain et al., 2023b).

Estimation of below-ground biomass (BGB)

Below-Ground Biomass was estimated to be 26% of AGB using the following formula:

$BGB = AGB \times 0.26$ (Surabhee et al., 2018)

Estimation of total biomass

Total biomass (TB) is the sum of AGB and BGB:

$TB = AGB + BGB$ (Dadhich et al., 2023)

Species composition and diversity

This study was rich in plant biodiversity, especially economically important woody tree plants. More than 40 different families encountered in this study with valuable indigenous tree species such as Milicia excelsa, Terminalia superba, and Irvingia gabonensis etc.

Data analysis and modelling

Estimation of (AGB)

In this study, aboveground biomass was estimated via a non-destructive approach using the volume (Newton's volume) and density (wood density) of the measured trees. Sacred groves hold high importance, as their natural counterparts are almost depleted. Indigenous and endemic species are found in sacred groves and have become a traditional conservation site without conscious practice of conservation by the local dwellers. Destructive sampling of biomass estimation is considered a taboo in sacred groves; hence, the non-destructive method is the only allowable and viable method of biomass estimation. We modelled the biomass for all combined tree species. The volume was determined using the Newton function (Equation 1) (Aghimien et al., 2020; Ojo et al., 2020; Ige, 2018). Then, the volume computed was converted to biomass using the wood density and an expansion factor (Equation 2), following Pajtik et al. (2011) and Chave et al. (2014).

Modelling and Developing Allometric Equations

Three allometric models were used in this study, and the technique used to fit the biomass equations was the OLS.

$$\ln(AGB) = \beta_0 + \beta_1 \ln(d) + \varepsilon \qquad \ldots\ldots. \qquad (3)$$

$$\ln(AGB) = \beta_0 + \beta_1 \ln(d)^2 + \varepsilon \qquad \ldots\ldots. \qquad (4)$$

$$\ln(AGB) = \beta_0 + \beta_1 \ln(d) + \beta_2 \ln(h) + \varepsilon \qquad \ldots\ldots. \qquad (5)$$

Where: AGB is aboveground biomass (kg), d is the diameter at breast height (Dbh) (cm), h is tree height (m), ln is the natural logarithm, and the values, β_0, β_1, and β_2 are model parameters to be estimated; and, ε is the error term: $\varepsilon \approx (0,^2)$.

The total carbon sequestered by each tree in the sacred groove across the study area was calculated by summing up all the above-ground biomass. The weight of carbon in the tree was multiplied by 3.67 to determine the weight of carbon dioxide sequestered (Sharma et al., 2014).

Evaluation statistics

The models were evaluated to test their plausibility and recommend them for further use. The three allometric models were assessed based on the R squared (R^2), root mean square error (RMSE) value, Akaike information criterion (AIC), Bayesian information criterion (BIC), and relative rank sum ΣR. Model selection was based on the criterion that the higher the R^2, the smaller the values of (RMSE), (AIC), and (BIC), the better the model, and hence it will be adjudged the best model (Oluwajuwon et al., 2022). Computations and statistical analyses were performed using R (R Core Team, 2020).

The various evaluation test criterion will be estimated using the following expression:

Table 1: Statistical evaluation

S/N	Model NAME	Model Acronym	Model Function	Equation Number
1	R-Squared	(R^2)	$R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$	6
2	Root mean square error	(RMSE)	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{n}}$	7
3	The Akaike information criterion	(AIC)	$AIC = n\ln\left(\frac{RSS}{n}\right) + 2p$	8
4	The Bayesian information criterion	(BIC)	$BIC = n\ln\left(\frac{RSS}{n}\right) + p \ln n$	9

Results and Discussion

Summary of the tree variables

A total of 241 trees were used for this study, of which 151 were from the Ekosodin sacred grove and 90 were from the Oza Nisi sacred grove (Tables 2 & 3). The minimum and maximum dbh values for the Ekosodin sacred grove were 3.0 and 113.20, respectively, while for the Oza Nisi sacred grove, the dbh values ranged from 1.90 to as high as 138.40 (Tables 2 & 3).

Fitting of the models

The data were transformed using the natural log form to reduce heteroscedasticity and this method has been typically adopted in many other biomass studies (Ganamé et al., 2021; Sawadogo et al., 2010). Three allometric models were used in this study, with dbh and total height as the predictor variables. All the models were highly significant (Tables 4 & 5), as the evaluation statistics revealed a good fit in biomass prediction across both sacred groves, except Model 3 in which the second predictor parameter constant was not significant (Table 4). Although the number of individual species in the Oza Nisi sacred grove (N = 90) was much less than that in the Ekosodin sacred grove (N = 151), it produced more biomass and sequestered more carbon than the Ekosodin sacred grove, with more density in terms of species diversity (Table 6).

Table 2: Summary statistics of tree variables in the Ekosodin Sacred Grove

Variables	Min	Max	Mean	S.E	S.D
Db(cm)	6.10	136.27	29.4388	2.05319	25.31345
Dbh(cm)	5.40	123.20	24.7721	1.91241	23.50011
Dm(cm)	3.00	113.20	20.8468	1.73430	21.38189
Dt(cm)	1.3	107.3	17.310	1.6238	20.0196
BA(m2)	0.002	1.192	0.09127	0.015111	0.186296

Vol(m3)	0.018	29.409	1.90596	0.357203	4.403897
T.ht(m)	1.45	32.15	11.3219	0.57912	7.13988
Biomass	0.02	29.82	1.9326	0.36220	4.46555
N = 151					

Table 3: Summary statistics of tree variables in the Oza Nisi Sacred Grove

Variables	**Min**	**Max**	**Mean**	**S.E**	**S.D**
Db(cm)	2.30	144.60	47.1251	3.51554	33.351
Dbh(cm)	1.90	138.40	40.1804	3.24251	30.761
Dm(cm)	1.20	130.40	34.5702	3.02363	28.68468
Dt(cm)	1.10	119.10	29.5710	2.78528	26.42345
BA(m2)	0.000	1.504	0.20029	0.029884	0.283504
Vol(m3)	.0025	42.5839	4.585490	0.7828440	7.4267101
T.ht(m)	0.03	61.10	17.3286	1.36421	12.94206
Biomass	0.00	43.18	4.6497	0.79380	7.53068
N = 90					

Table 4: Pooled species models fitted for the aboveground biomass of the Ekosodin Sacred Grove

Dependent variable/ Model	**Independent variable**	**Parameter estimates**			**R2**	**RMSE**	**BIC**	**AIC**
		b_o	**b_1**	**b_2**				
$\ln(AGB)(1)$	$\ln(d)$	-6.964***	2.123***	-	0.979***	0.0635	-401.16	89.50
$\ln(AGB)(2)$	$\ln(d)^2$	-3.952***	0.346***	-	0.970***			
$\ln(AGB)(3)$	$\ln(d)$ & $\ln(h)$	-6.978***	2.106***	0.028^{ns}	0.979***			

AGB: Aboveground biomass, ln: natural logarithm, d: Diameter at breast height, h: Tree height, Adjusted R^2: adjusted Coefficient of determination, RMSE: Root mean square error, BIC: Bayesian Information Criterion, AIC= Akaike Information Criterion, b_o, b_1, and b_2: regression coefficients, (the least indicates the best model); (***), significant at $\alpha = 0.005$; ns, non-significant.

Table 5: Pooled species models fitted for the aboveground biomass of the Oza Nisi Sacred Grove

Dependent variable	**Independent variable**	**Parameter estimates**			**R2**	**RMSE**	**BIC**	**AIC**
		b_o	**b_1**	**b_2**				
$\ln(AGB)$	$\ln(d)$	-7.051***	2.150***	-	0.941***	0.2284	-119.39	89.51
$\ln(AGB)$	$\ln(d)^2$	-4.168**	0.356***	-	0.925***			
$\ln(AGB)$	$\ln(d)$ & $\ln(h)$	-6.872***	2.040***	0.097***	0.948***			

AGB: Aboveground biomass, ln: natural logarithm, d: Diameter at breast height, h: Tree height, Adjusted R^2: adjusted Coefficient of determination, RMSE: Root mean square error, BIC: Bayesian Information Criterion, AIC= Akaike Information Criterion, b_o, b_1, and b_2: regression coefficients, (the least indicates the best model), (***), significant at $\alpha = 0.005$; ns, non-significant.

Table 6: Output of biomass and carbon sequestration estimation

Sacred Grove	AGB (kg/ha)	BGB (kg/ha)	TB (kg/ha)	CO_2 Sequestered
Ekosodin	293.76	76.38	370.14	1,358.40
Oza Nisi	418.47	108.80	527.27	1535.78
Total	**712.23**	**185.18**	**897.41**	**2,894.18kg/ha**

AGB, Above ground biomass, BGB, Below ground biomass, TB, Total biomass

Discussion

Alade, 2023 agreed that "The carbon sequestration rate and potential of most of the forests in a typical developing tropical country like Nigeria have been significantly decimated over the years" (Mitchard, 2018), due to several deforestation and degradation activities in these forest estates. The ever-increasing illegal logging activities have made the remaining reserves a shadow of itself or are now hideouts for perpetrating crime. A shift to community-based protected areas, such as sacred groves, would provide a solution to the removal of carbon from the atmosphere. In this study, we developed all-species combined allometric models to predict the aboveground biomass in the sacred groves of the rain forest site in Nigeria. The models were fitted using the linear (logarithmic) form. To reduce the variance due to homoscedasticity, the data were ln-transformed. This methods has been well established.

Diameter at breast height (BH) is one of the easily measured variables in resource inventory (Balima et al., 2020), and BH has been mostly used as the principal or, choice predictor variable in fitting allometric models for estimating woody tree biomass (Hossain et al., 2023b;). One of the major reasons for this is that DBH accounts for about 95% of the aboveground biomass Chave et al. (2005). The use of only DBH in the work of Alade et al ., (2023) gave less reliable estimates in the allometric model, which is contrary to the results of this study, in which the use of only DBH gave significantly better estimates across both sacred groves. The total height predictor performed poorly as a predictor variable in Model 3, which gave a non-significant estimate. However, the overall performance of DBH and the total height was good based on the evaluation statistics, which had a high R^2, low RMSE, AIC, and BIC. The biomass from the Oza Nisi sacred grove (AGB 418.47 kg/ha) was significantly higher than that from the Ekosodin sacred grove (AGB 293.76 kg/ha), even though the former had lower species composition density. This may be because the Oza Nisi sacred grove had larger DBH sizes and taller trees with the maximum heights reaching 138.40cm and 61.10m, respectively, while the maximum DBH and total height in the other sacred grove were 123.20cm and 29.82m, respectively: This result agrees with the findings of Baishya et al., (2009) from India and Djuikouo et al., (2010) from Kenya who both opined that stand parameters such as tree height and DBH show a positive correlation; larger diameter size with a corresponding tall height leads to higher aboveground biomass and wood production.

The carbon sequestration potential of the selected sacred groves is very promising as a climate change mitigation solution, as it sequestered CO_2 to a large amount of (2,894.18kg/ha), with the larger amount coming from the Oza Nisi sacred grove (1535.78kg/ha). This agrees with Shrestha et al., (2016), who opined that sacred groves can protect forest ecosystems and might help reduce climate change through carbon sequestration. Apart from the global benefit of these sacred groves serving as climate change mitigation strategy, the concept of carbon sequestration of trees in these study sites may also be a primary role of carbon estimation, which in turn may lead to the estimation of carbon credit serving as a major source of income to the local people. A carbon credit represents one tonne (1000 kilogrammes) of carbon dioxide (CO_2) that has been either removed from the atmosphere or prevented from being released. It represents the amount of CO_2 a tree can store (like a permit to pollute less), and those credits can be sold to companies that need to offset their emissions into the atmosphere.

Conclusions and Recommendations

This study demonstrates that sacred groves in Edo State, Nigeria, serve as important reservoirs of aboveground biomass and carbon, highlighting their critical role in the provision of ecosystem services, particularly climate change mitigation. The findings reveal that groves protected by traditional beliefs and community-based conservation practices possess substantial aboveground biomass and carbon stocks, which are comparable to those of more formally protected forest areas. The variation in biomass density and carbon sequestration potential observed among groves underscores the influence of local management practices, species composition, and disturbance regimes.

The dominance of ecologically valuable tree species, such as Milicia excelsa, Terminalia superba, and Irvingia gabonensis, further reinforces the importance of sacred groves as biodiversity hotspots. Considering the increasing deforestation and degradation of natural forests across Nigeria, the conservation of sacred groves presents a viable, community-driven strategy for climate action and forest preservation. Future research should explore the long-term dynamics of biomass accumulation in sacred groves and assess the sociocultural drivers that influence their conservation status. Strengthening the collaboration between local communities, researchers, and policymakers is crucial to safeguarding these groves and amplifying their ecological benefits.

Ultimately, sacred groves represent a synergistic opportunity to bridge indigenous knowledge and scientific conservation, contributing to Nigeria's commitment to sustainable development and global climate change.

Acknowledgements

The authors express their gratitude to both communities for granting permission into the sacred groves and, for the inventory work that, has made this study possible.

Financial Disclosure:

The authors declare that this research work did not receive any external funding.

Conflict of Interest:

The authors declare that there is no competing interest exists.

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