LAUTECH Journal of Civil and Environmental Studies DOI: 10.36108/laujoces/6202.61.0210
Volume XVI, Issue II; June, 2026

Biomass and Carbon Sequestration Potential of Orisunbare–Apoti Forest Reserve, Osun State, Nigeria

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Abstract

Orisunbare–Apoti Forest Reserve is an important remnant forest Reserve in Osun State, southwestern Nigeria. However, field-based estimates of its biomass and carbon stock have been limited. This study assessed stand structure, biomass, carbon stock, and carbon sequestration potential. A total of ten 20 m × 20 m plots established across the reserve. All trees with Diameter at Breast Height (Dbh) ≥ 5 cm were measured using a diameter tape, while tree height was measured using a Haga altimeter. Species-specific wood density values were obtained from global databases. Above-ground biomass (AGB) was estimated using the pantropical allometric model while belowground biomass, total biomass, carbon stock, and CO_2 equivalent were derived using standard forest carbon methods. Results showed variability in stand structure. Tree density ranged from 12 to 21 trees per plot, mean Dbh from 37.30 to 74.08 cm, mean height from 8.16 to 11.09 nm, and basal area from 52.89 to 203.21 m² ha⁻¹. Total biomass was 40,635 kg, carbon stock was 19,290 kg, and CO_2 equivalent was 70,820 kg. Linear regression indicated that basal area had a highly significant positive effect on carbon stock ($\beta = 11.13$, $p = 0.0015$). Similarly, multiple regression confirmed basal area as the strongest predictor of carbon stock ($\beta = 9.84$, $p = 0.009$), both significant at the $\alpha = 0.05$ significant level. The study concludes that the reserve has notable carbon sequestration potential and can support Reducing Emissions from Deforestation and Forest Degradation (REDD+) planning, forest conservation, and long-term monitoring in Southwestern Nigeria.

Keywords: Carbon sequestration; Forest Carbon stock; Climate change mitigation; Tropical Forest reserve; REDD+

Introduction

Tropical forest reserves are increasingly recognised as critical reservoirs of biodiversity and significant carbon sinks in the global effort to mitigate climate change (Komolafe *et al*., 2020; FAO, 2022). In Nigeria, deforestation and land-use change continue to reduce forest cover, making the quantification of biomass and carbon stock essential for evidence-based forest management and climate change mitigation planning (Ogunfolu *et al*., 2022). Earlier studies have demonstrated that even small- to medium-sized forest reserves can store substantial amounts of carbon when characterized by mature tree stands and relatively low levels of disturbance (Komolafe *et al*., 2020). Studies conducted in Ibodi Monkey Forest and Oba Hill Forest Reserve revealed that managed and semi-natural forest stands can accumulate aboveground carbon stocks in the range of 100–200 Mg C ha^{-1}, signifying the critical role of stand structure and species composition in enhancing carbon sequestration capacity (Komolafe *et al*., 2020; Ogunfolu *et al*., 2022). Despite these advances, stand-level data on biomass and carbon stocks remain limited for many protected forest landscapes in Southwestern Nigeria, including the Orisunbare–Apoti Forest Reserve. Although this reserve makes up an important forest network in Osun State sizable portion of the remaining Osun State Forest network, it lacks up-to-date, field-based estimates of tree biomass, carbon stock, and carbon sequestration potential, despite growing demands from Reducing Emissions from Deforestation and Forest Degradation (REDD+) policies and nature-based solutions for precise, local data (IPCC, 2023).

Subsequently, this study addresses these gaps by characterizing stand structure and tree species composition using inventory method, estimating above- and below-ground biomass and total carbon stocks using the Chave *et al*. (2014) pantropical allometric equation, selected for its robustness across moist forests with wood density data; assessing sequestration potential from biomass estimates and stand dynamics; and analyzing relationships between structural attributes (diameter at breast height distribution, basal area, tree density) and carbon storage. Results will provide baseline data for Southwestern Nigerian forests, inform state-level mitigation planning, and support long-term monitoring of Orisunbare–Apoti and analogous reserves.

Methodology

Study Area

Orisunbare–Apoti Forest Reserve lies in Oriade (Ori-Ade) Local Government Area of Osun State, in Southwestern Nigeria. The reserve borders the rural communities of Orisunbare and Apoti. Geographically, it is situated in the humid tropical ecological zone typical of Southern Osun State. The state experiences a distinct bimodal rainfall pattern, with the wet season extending from April to October and annual rainfall reaching up to about 1,800 mm. The dry season occurs from November to March, with relatively lower precipitation. Mean temperatures range from about 18 °C to 30 °C, typical of the tropical lowland forest belt of Nigeria. The terrain around the reserve is gently undulating, with low hills and shallow valleys, and the soils are predominantly lateritic, varying from loamy to clayey textures depending on slope position and past land-use history (Asifat *et al*., 2019).

Vegetation in the reserve is largely semi-deciduous rainforest, mixed with patches of secondary regrowth that reflect historical human disturbance. The forest is surrounded by a mosaic of farmland, fallow land, and regenerating forest, which influence species diversity, edge effects, and regeneration patterns (Asifat *et al.*, 2019). Human activities place considerable pressure on the reserve: small-scale farming, fuelwood collection, charcoal production, and selective logging are common in and around the reserve, contributing to forest fragmentation and habitat degradation. The local Ijesa (Yoruba) communities depend heavily on forest resources for their livelihood.

Data collection

Plot establishment

A field inventory of trees was conducted to estimate structural parameters, biomass, and carbon stocks. Ten permanent plots of 20 m × 20 m (0.04 ha each) were established using a stratified random sampling approach to capture spatial variation in forest structure across the reserve. The plots were laid out along representative transects that cross different disturbance gradients and topographic positions within the reserve.

Tree measurements

Within each plot, all woody stems with a diameter at breast height (Dbh) ≥ 5 cm were enumerated and measured. Dbh was measured at 1.3 m above ground using a diameter tape. Total tree height was measured using a Hagar altimeter. Each tree was identified to species level in the field using taxonomic keys and expert consultation; voucher specimens were collected for species that could not be identified with certainty in the field and later verified at the herbarium. The Dbh and height measurements obtained for each tree provided the essential biometric data required for calculating basal area, volume, biomass, and carbon stocks for the reserve.

Wood density data

Species-specific wood density (ρ)

Species-specific wood density (ρ) values (in g cm^{-3}) were sourced from reputable and widely used databases to ensure accuracy and consistency in biomass estimation. The Global Wood Density Database (Zanne *et al*., 2009) served as the primary source owing to its extensive species coverage and frequent application in tropical forest studies across Nigeria and West Africa (Chave *et al*., 2014). Where species-specific values were unavailable or incomplete, additional data were obtained from African wood-density compilations to better reflect the characteristics of locally occurring tree species and improve the precision of carbon stock estimates.

Data estimation

Forest structure analysis

The forest structure of Orisunbare–Apoti Forest Reserve was characterized using standard phytosociometric and stand-structure parameters, including basal area, tree density, and mean height, computed per plot and then scaled to hectares.

Basal area

The basal area of all trees in the sample plots was calculated using the formula:

$$\text{BA (m}^2\text{)} = \frac{\pi D^2}{4} \quad (1)$$

Where; D = Diameter at breast height; π is the constant: 3.142.

The total basal area for each plot was obtained by summing the basal area of all trees recorded within that plot.

Biomass and carbon estimation

Tree biomass was estimated using allometric equations appropriate for humid tropical rainforest species in West Africa, particularly those incorporating Dbh, height, and wood density (Chave *et al*., 2014; Hamzath Kora *et al*., 2018). Biomass values were initially calculated per tree and then aggregated per plot and scaled to per-hectare values.

Above-ground biomass (AGB)

Above-ground biomass (AGB) of individual trees was estimated using the widely applied pantropical model developed by Chave *et al*. (2014):

$$\ln(\text{AGB}) = -2.977 + 0.976 \ln(\rho D2H) \quad (2)$$

where: ρ = wood density (g cm^{-3}) for each species, D = diameter at breast height (cm), and H = total tree height (m). The resulting AGB was expressed in kilograms per tree and then summed across all trees per plot.

Below-ground biomass (BGB)

Below-ground biomass (BGB) was estimated as a proportion of above-ground biomass using the root-to-shoot ratio (root:shoot) recommended for tropical forests by the IPCC (2006):

$$BGB = r \times \text{AGB} \quad (3)$$

where r is the root-to-shoot ratio, assumed to be 0.20 (i.e., 20% of AGB). This value is consistent with empirical estimates for many tropical lowland forests and is widely used in national-level biomass and carbon assessments.

Total biomass

Total biomass (TBiomass) per tree was obtained by summing the above-ground and below-ground biomass:

$$\text{TBiomass} = \text{AGB} + \text{BGB} \quad (4)$$

Per-plot biomass values were converted to megagrams per hectare (Mg ha^{-1}) using the standard procedure for area-based scaling outlined by Salas *et al*. (2017), assuming each 20 m × 20 m plot represents 0.04 ha

$$\text{TBiomass} = \frac{\sum(AGB+BGB)}{0.04} \quad (5)$$

Carbon stock estimation

Carbon stored in tree biomass (C) was estimated using the allometric approach described by Kauffman and Donato (2012) and applied in recent Nigerian forest assessments (Dada *et al.*, 2024). Carbon fractions were applied separately to the above-ground and below-ground components, assuming that 50% of dry biomass is carbon for both compartments:

$$\text{Above-ground carbon (AGC)} = 0.5 \times \text{AGB} \quad (6)$$

$$\text{Below-ground carbon (BGC)} = 0.2 \times \text{BGB} \quad (7)$$

Total carbon stock per tree was then:

$$Cs = AGC + BGC \quad (8)$$

Carbon dioxide equivalent (CO_2e) estimation

The carbon stock values were converted to their carbon dioxide equivalent (CO_2e) using the standard molecular-weight conversion factor recommended by Bhatta *et al*. (2018):

$$CO_2e = \text{Estimated Cs} \times \frac{44}{12} \quad (9)$$

where C is the estimated carbon stock (kg C ha^{-1}) and CO_2e is expressed in kg CO_2 ha^{-1}. This conversion provides a clearer understanding of the amount of carbon dioxide that can be sequestered or emitted as a result of changes in biomass within the reserve.

Statistical Analysis

Descriptive statistics was used to summarize stand density, mean Dbh, mean height, and basal area across plots. Linear regression and multiple regression were used to test the relationship between basal area, mean Dbh, mean height, and carbon stock. Analysis of Variance (ANOVA) was used to determine the statistical significance of the regression models at the $\alpha = 0.05$ significant level.

Results and Discussion

Stand Structure and Tree Growth Characteristics

Table 1 shows the distribution of tree population, mean diameter at breast height (Dbh), mean tree height, basal area (BA), and tree density across the sampled plots.

Tree density ranged from 12 trees in Plot 6 to 21 trees in Plot 2. Mean Dbh varied substantially among plots, ranging from 37.30 cm in Plot 3 to 74.08 cm in Plot 9. Mean tree height ranged from 8.16 m to 11.09 m, while basal area varied from 52.89 m² ha^{-1} in Plot 3 to 203.21 m² ha^{-1} in Plot 5. The total tree population recorded across all plots was 157 individuals, with an overall tree density of 1,291.95 trees ha^{-1}.

Tree density ranged from 12 to 21 trees per plot, with Plot 2 showing the highest density and Plot 6 the lowest. This pattern suggests that some plots may represent more active regeneration, while others may have undergone thinning, extraction, or stand maturation. In tropical forest ecology, higher stem density often indicates secondary regrowth following disturbance, whereas lower density can reflect self-thinning in older stands or depletion through anthropogenic pressure (Ige and Ajiboye, 2024). Mean Dbh showed a strong spread from 37.30 cm in Plot 3 to 74.08 cm in Plot 9, indicating marked differences in diameter class structure. Plots with higher mean Dbh, especially Plots 5, 6, 9, and 10, are likely dominated by mature or large-stemmed trees that contribute disproportionately to biomass and carbon storage. Mean tree height varied from 8.16 to 11.09 m, pointing to moderate vertical stratification across the reserve. Taller plots, particularly Plots 8, 9, and 10, suggest better canopy development and stronger competitive dominance for light capture. Canopy height is ecologically important because it influences light interception, productivity, habitat complexity, and stand carbon dynamics (Kayombo *et al*., 2022). Basal area ranged from 52.89 to 203.21 m² ha⁻¹, with higher values observed in Plots 5 and 9, indicating structurally mature stands dominated by large-diameter trees. Basal area is widely recognized as a key indicator of stand structure and biomass, with higher values typically associated with older, less disturbed forests where large trees contribute disproportionately to stand volume and carbon storage (FAO, 2018).

Table 1: Stand Structure and Tree Growth Characteristics Across Sample Plots

Plot	N0. of trees	Mean Dbh	Mean Ht	BA (m²/plot)	BA (m²/ha)	Tree density (tree/ha)
1	17	10.69	44.01	8.97	3.43	83.42
2	21	13.21	57.24	10.2	6.3	157.512
3	16	10.06	37.3	8.16	2.12	52.89
4	16	10.06	47	9.24	3.27	81.67
5	16	10.09	72.75	9.93	8.13	203.21
6	12	7.55	67.53	9.71	5.64	140.91
7	14	8.81	51.59	8.56	3.77	94.22
8	16	10.08	65.41	10.29	6.13	153.27
9	16	10.06	74.08	10.66	7.823	195.47
10	13	8.18	67.08	11.09	5.8	129.38
Total	157	98.9	583.99	96.81	51.7	1291.95

Plot-Level Biomass, Carbon Stock and CO_2 Sequestration Potential

Table 2 shows the estimated aboveground biomass (AGB), belowground biomass (BGB), total biomass, carbon stock (Cs), and carbon dioxide equivalent (CO_2e) for each plot. Aboveground biomass ranged from 1,252 kg in Plot 1 to 5,612 kg in Plot 5. Carbon stock varied from 713 kg in Plot 1 to 3,193 kg in Plot 5, while CO_2 sequestration potential ranged between 2,620 and 11,720 kg CO_2e. The reserve contained 33,863 kg of aboveground biomass and 6,772 kg of belowground biomass. Total carbon stock was estimated at 19,290 kg, corresponding to 70,820 kg CO_2 equivalent.

Total biomass and carbon stock recorded in this study are relatively higher compared with many other forest ecosystems in Southwestern Nigeria. Total biomass (1,015.88 Mg ha⁻¹) and carbon stock (482.25 Mg C ha⁻¹) recorded in this study are relatively high compared to other forest ecosystems in Southwestern Nigeria. For example, studies in Ise-Ekiti and Omo Forest Reserves reported carbon stocks ranging between 150 and 350 Mg C ha⁻¹ depending on disturbance intensity. Carbon storage in the Strict Nature Reserve of Omo Biosphere Reserve has been reported as substantially influenced by forest condition and disturbance history (Dada *et al*., 2024; Ubaekwe, 2020). The comparatively higher values observed in this study suggest the presence of mature stands and relatively intact forest patches.

The substantial biomass accumulation observed in this study may be attributed to the presence of large-diameter trees and relatively intact forest patches. Mature tropical forests generally store larger amounts of carbon because biomass increases exponentially with tree size (Chave *et al*., 2014). Consequently, conservation of existing large trees within the reserve is critical for maintaining ecosystem carbon stocks.

The estimated CO_2 sequestration potential further demonstrates the significance of the reserve in climate change mitigation. These findings support the growing recognition of tropical forest reserves as nature-based solutions capable of contributing to national carbon reduction targets and REDD+ implementation programmes (FAO, 2022; IPCC, 2023).

Table 2: Aboveground and Belowground Biomass, Carbon Stock, and CO_2 Sequestration by Plot

Plot	AGB (kg)	BGB (kg)	TBiomass (kg)	Cs (kg)	CO_2e(kg)
1	1,252	250	1,502	713	2,620
2	3,805	761	4,566	2,164	7,950
3	2,298	460	2,758	1,311	4,810
4	3,098	620	3,718	1,766	6,490
5	5,612	1,122	6,734	3,193	11,720
6	3,398	680	4,078	1,937	7,110
7	2,998	599	3,597	1,710	6,270
8	3,698	740	4,438	2,105	7,740
9	4,202	840	5,042	2,395	8,790
10	3,502	700	4,202	1,996	7,320
Total	33863	6772	40635	19290	70820

Table 3 summarizes total biomass components and converts them into per-hectare values with total biomass of 1,015.88 t ha^{-1} and carbon stock of 482.25 t C ha^{-1}. Aboveground biomass dominates the carbon pool, indicating that woody stems constitute the major carbon reservoir, while belowground biomass contributes a smaller but essential fraction. This is consistent with tropical forest carbon allocation patterns (Chave *et al*., 2014; IPCC, 2019).

The high carbon stock and CO_2 equivalent (1,770.50 t CO_2 ha^{-1}) suggest that the forest functions as a significant carbon sink with strong potential for climate change mitigation. Similar studies in tropical forests have shown that intact or semi-intact stands with large-diameter trees tend to accumulate higher carbon stocks due to greater basal area and stand maturity (Dada *et al*., 2024; Wang *et al*., 2024). This highlights the ecological importance of the reserve for regional carbon sequestration, climate regulation, and REDD+ implementation (FAO, 2022; IPCC, 2023).

Table 3: Summary of Biomass, Carbon Stock, and CO_2 Sequestration per Hectare

Variable	**Total (kg)**	**t/ha**
AGB	33,863	846.58
BGB	6,772	169.3
Total Biomass	40,635	1,015.88
Carbon Stock	19,290	482.25
CO_2e	70,820	1,770.50

Relationship between Stand Structure and Carbon Stock

Table 4 presents the ANOVA results for the regression model examining the effect of basal area on carbon stock. The model was statistically significant at the 5% probability level ($F_{1,8} = 22.26$, $p = 0.0015$; $\alpha = 0.05$), indicating that basal area significantly explains variation in carbon stock across the study plots. This confirms that stand structural variation strongly influences carbon storage within the reserve.

Table 4: ANOVA for Regression of Basal Area vs Carbon Stock

Source	Df	SS	MS	F	p-value
Regression	1	4,177,458	4,177,458	22.26	0.0015
Residual	8	1,500,842	187,605		
Total	9	5,678,300			

Table 5 presents the results of the linear regression analysis between basal area and carbon stock. At the ($\alpha = 0.05$) significance level, basal area had a significant positive effect on carbon stock ($\beta = 11.13$, $t = 4.72$, $p = 0.0015$). This implies for every 1 m^2 increase in basal area, carbon stock increases by approximately 11.13 kg**.** The intercept was not statistically significant ($p = 0.12$), suggesting that carbon stock is primarily influenced by variations in basal area rather than the baseline value represented by the intercept. The t-value of 4.72 for basal area confirms its strong predictive power. This confirms that stand structural variation strongly influences carbon storage within the reserve.

Table 5: Linear Regression Summary

Parameter	Estimate	Std. Error	t-value	p-value
Intercept	490.66	281.32	1.74	0.12
Basal Area	11.13	2.36	4.72	0.0015

Table 6 presents the multiple regression analysis of carbon stock in relation to basal area, mean diameter at breast height (Dbh), and mean height. At the ($\alpha = 0.05$) significance level, basal area ($\beta = 9.84$, $p = 0.009$) and mean Dbh ($\beta = 4.21$, $p = 0.05$) had significant positive effects on carbon stock, whereas mean height ($\beta = 1.37$, $p = 0.26$) was not significant. These results indicate that stand structural characteristics, particularly basal area and Dbh, are the primary determinants of carbon storage in the reserve.

Table 6: Multiple Regression of Carbon Stock on Stand Structural Attributes

Predictor	β (Estimate)	Std. Error	t-value	p-value
Intercept	312.45	295.2	1.06	0.32
Basal Area (BA)	9.84	2.75	3.58	0.009
Mean Dbh	4.21	1.88	2.24	0.05
Mean Height	1.37	1.12	1.22	0.26

Model form: $C=\beta 0+\beta 1(DBH)+\beta 2(Height)+\beta 3(BA)$

The strong positive relationship between basal area and carbon stock confirms the importance of stand structural attributes in determining forest carbon accumulation and variation in biomass accumulation. his aligns with recent findings that stand structural attributes, particularly basal area and Dbh, are strong predictors of carbon sequestration in tropical forests (Wang *et al*., 2024; Fatimah *et al*., 2024). The positive contribution of Dbh to carbon storage further supports previous studies showing that large-diameter trees account for a disproportionate share of forest biomass and carbon pools (Chave *et al*., 2014; Dada *et al*., 2024). The strong dependence of carbon stock on basal area suggests that conservation strategies should prioritize protection of large-diameter trees, reduce illegal logging and fuelwood extraction, and promote assisted natural regeneration (Dada *et al*., 2024; FAO, 2022). The marginal contribution of tree height indicates that horizontal stand structure plays a more dominant role than vertical structure in biomass accumulation. These findings show that the reserve has meaningful carbon sequestration potential and can contribute to REDD+ implementation and climate change mitigation efforts in Osun State.

Conclusion

This study has proven that Orisunbare–Apoti Forest Reserve shows clear structural heterogeneity, with variation in tree density, diameter, height, and basal area across plots. The reserve stores appreciable biomass and carbon, with carbon stocks comparable to or exceeding those reported in similar forest ecosystems in Southwestern Nigeria. Basal area and Dbh were identified as the primary drivers of carbon storage, showing the ecological importance of structurally complex forests. This study recommends sustainable forest management practices aimed at conserving large trees and minimizing anthropogenic disturbances. Given its high carbon storage capacity, the reserve represents a valuable asset for climate change mitigation initiatives, particularly under REDD+ frameworks.

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