

# Quantitative Assessment of Carbon Sequestration Potential and Biomass Accumulation in Selected Forest Ecosystems of Southern Nigeria

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**Abstract:** This study quantitatively assessed biomass accumulation and carbon sequestration potential across selected forest ecosystems in Southern Nigeria. The ecosystems evaluated included Tropical Rainforest, Freshwater Swamp Forest, Mangrove Forest, Secondary Forest, and Mixed Forest. Field inventory data on diameter at breast height (DBH), tree height, species composition, and density were collected and used to estimate aboveground and belowground biomass through established allometric equations. Carbon stock was derived using standard conversion factors, while carbon dioxide equivalent ( $CO_2e$ ) was computed to determine sequestration potential. Results revealed significant variation in forest structure, biomass accumulation, and carbon storage among the ecosystems. The Tropical Rainforest recorded the highest biomass ( $567.4 \pm 38.9 \text{ Mg ha}^{-1}$ ), carbon stock ( $283.7 \pm 19.5 \text{ Mg C ha}^{-1}$ ), and carbon sequestration potential ( $1040.2 \pm 71.5 \text{ Mg CO}_2 \text{ ha}^{-1}$ ), followed by Freshwater Swamp and Mangrove Forests. The Secondary Forest exhibited the lowest biomass and carbon stock despite having the highest tree density, indicating that tree size and forest maturity are stronger determinants of carbon storage than stem abundance. Correlation and regression analyses showed strong positive relationships between carbon stock and forest structural variables, particularly basal area ( $r = 0.95$ ) and DBH ( $r = 0.93$ ). The regression model explained 89.1% of the variation in carbon stock, confirming that forest structure and species diversity are key predictors of carbon sequestration potential. The study concludes that Southern Nigerian forest ecosystems are significant carbon sinks with strong potential for climate change mitigation.

*It recommends the conservation of mature forest stands, restoration of degraded ecosystems, and integration of biodiversity conservation into climate policy frameworks to enhance long-term carbon storage and ecosystem sustainability.*

**Keywords:** Carbon sequestration, biomass accumulation, tropical forests, forest ecosystems, Southern Nigeria

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## 1.0 Introduction

Climate change has emerged as one of the most pressing environmental challenges of the twenty-first century, primarily driven by the increasing concentration of greenhouse gases in the atmosphere, particularly carbon dioxide ( $CO_2$ ). Anthropogenic activities such as deforestation, industrialization, urbanization, land-use change, and fossil fuel combustion have significantly altered the global carbon cycle, resulting in rising global temperatures, changing precipitation patterns, biodiversity loss, and ecosystem degradation. Forest ecosystems play a critical role in mitigating climate change through their capacity to absorb atmospheric carbon dioxide and store it in living biomass, dead organic matter, and soil

carbon pools. Globally, forests constitute the largest terrestrial carbon sink, accounting for approximately 90% of all living terrestrial biomass and serving as an important mechanism for reducing atmospheric carbon concentrations (Ajayi, 2021). Consequently, quantifying biomass accumulation and carbon sequestration potential in forest ecosystems has become an essential component of climate change mitigation strategies, sustainable forest management, and carbon accounting initiatives.

Biomass accumulation represents the amount of organic matter produced and stored within forest vegetation, while carbon sequestration refers to the process through which atmospheric carbon dioxide is captured and stored in biomass and soil over time. The relationship between biomass and carbon storage is fundamental because carbon constitutes approximately 50% of dry biomass in most tree species. Therefore, accurate estimation of forest biomass provides a reliable basis for assessing carbon stocks and sequestration potential. Forest ecosystems with high biomass accumulation generally possess greater carbon storage capacities and contribute significantly to reducing greenhouse gas concentrations. In tropical regions, where vegetation productivity is generally high, forests serve as major reservoirs of terrestrial carbon and offer substantial opportunities for climate change mitigation.

Several studies have demonstrated the importance of forests and tree species in carbon sequestration across different ecological zones. Ajayi (2021) assessed the carbon sequestration potential of selected urban tree species in Ondo State, Nigeria, and reported that *Gmelina arborea* exhibited the highest carbon sequestration capacity among the species investigated. The study highlighted the contribution of urban forests to carbon storage and emphasized the need for species-specific assessments to improve carbon accounting.

Similarly, Eneji *et al.* (2014) investigated carbon storage potential in tropical forest reserves and tree species in Benue State, Nigeria, and found significant variations among species, with *Persea americana* exhibiting the highest carbon sequestration potential. Their findings underscored the influence of tree characteristics such as canopy structure and vegetation density on carbon storage.

Studies conducted in forest reserves have further demonstrated substantial variability in carbon stocks among vegetation types. Jibrin *et al.* (2014) quantified carbon stocks across six vegetation communities in Kpashimi Forest Reserve, Niger State, and reported that riparian forests possessed the highest carbon stock density, followed by savanna woodland and degraded forest ecosystems. The study revealed that deforestation and forest degradation had resulted in significant carbon emissions over twenty years, thereby highlighting the potential benefits of forest restoration for enhancing carbon sequestration. Similar findings were reported by Abdullahi *et al.* (2014), who emphasized the feasibility of carbon offset projects in forest ecosystems with high restoration potential.

Species-specific assessments have also contributed significantly to understanding forest carbon dynamics. Adedokun *et al.* (2019) evaluated the carbon sequestration potential and aboveground biomass of *Triplochiton scleroxylon* in Gambari Forest Reserve and observed that larger trees stored substantially more carbon than smaller individuals. Likewise, Odiwe *et al.* (2017) estimated biomass and carbon stocks of five tree species in a secondary forest ecosystem and found significant differences among species, with *Celtis zenkeri* exhibiting the highest biomass accumulation and carbon stock. These studies demonstrated that tree size, species composition, diameter at breast height (DBH),



and height are important determinants of biomass accumulation and carbon storage.

Recent investigations have expanded carbon sequestration assessments beyond natural forests to plantations, agroforestry systems, and mixed vegetation stands. Okwu-Abolo *et al.* (2026) examined carbon accumulation across a fifty-year chronosequence rubber plantation in Nigeria and reported substantial increases in biomass and carbon stocks with plantation age. The study showed that approximately 85.5% of total carbon was stored in aboveground biomass, highlighting the significant contribution of plantation forests to climate change mitigation. Similarly, Yangaza and Andrew (2026) evaluated carbon stocks of avocado trees in Tanzanian agroforestry systems and reported significant spatial variations in biomass and carbon storage among districts. Their findings demonstrated the potential of agroforestry systems as important carbon sinks while simultaneously supporting livelihoods and ecosystem services.

Urban and mixed forest ecosystems have also attracted increasing attention due to their potential contributions to carbon sequestration. Ahmed *et al.* (2025) assessed urban forest structure and carbon storage in Kano Metropolis and reported total carbon stocks exceeding 3,900 tons, with larger trees contributing disproportionately to total biomass. Egonmwan and Samuel (2025) evaluated carbon sequestration and carbon credit potential in a mixed vegetation stand in southern Nigeria and estimated a carbon sequestration capacity capable of offsetting the annual carbon emissions of approximately 571 individuals. Their study further highlighted the economic opportunities associated with carbon markets and ecosystem service payments.

Advancements in remote sensing and geospatial technologies have enhanced the monitoring of carbon dynamics across landscapes. Shamaki *et al.* (2025) assessed

carbon sequestration dynamics in the Southern Guinea Savannah of Nigeria using multi-date satellite imagery and reported significant temporal fluctuations in carbon stocks resulting from vegetation recovery, deforestation, and land degradation. Similarly, Gilang Qur'ani *et al.* (2024) emphasized the importance of understanding the interactions between natural and anthropogenic drivers of carbon dynamics, particularly in sensitive ecosystems such as mangrove forests. Their review highlighted the need for integrated assessments that consider climate variability, land-use changes, and species diversity when evaluating carbon storage and sequestration.

Despite the growing body of literature on biomass accumulation and carbon sequestration, significant knowledge gaps remain. Most studies in Nigeria have focused on individual tree species, urban forests, plantations, agroforestry systems, or specific forest reserves. Many assessments have been restricted to aboveground biomass, with limited consideration of belowground biomass and ecosystem-level carbon storage. Furthermore, comparative studies involving multiple forest ecosystems within Southern Nigeria remain scarce despite the region's ecological diversity, which includes tropical rainforest, freshwater swamp forest, mangrove forest, secondary forest, and mixed vegetation systems. Existing studies have also reported considerable variability in carbon stocks due to differences in species composition, forest structure, age, management practices, and environmental conditions, indicating the need for more comprehensive quantitative assessments. Consequently, there is insufficient information regarding how biomass accumulation and carbon sequestration vary among different forest ecosystems in Southern Nigeria and the factors responsible for such variations.

The aim of this study is therefore to quantitatively assess the carbon sequestration



potential and biomass accumulation of selected forest ecosystems in Southern Nigeria. Specifically, the study seeks to estimate aboveground and belowground biomass, quantify carbon stocks and carbon dioxide sequestration capacities, compare carbon storage potentials among forest ecosystems, and evaluate the influence of forest structural characteristics on biomass accumulation and carbon sequestration.

The significance of this study lies in its contribution to climate change mitigation, sustainable forest management, and environmental policy development. The findings will provide reliable baseline data for carbon accounting, biodiversity conservation, and ecosystem management initiatives in Southern Nigeria. The study will also support national commitments to greenhouse gas reduction, climate adaptation, and international frameworks such as the Paris Agreement and REDD+ programmes. Furthermore, the results will provide scientific evidence for afforestation, reforestation, and forest restoration projects while highlighting opportunities for participation in emerging carbon markets and ecosystem service payment schemes. By generating quantitative information on biomass accumulation and carbon sequestration across different forest ecosystems, the study will contribute to an improved understanding of the role of Southern Nigerian forests in maintaining ecological stability and mitigating global climate change.

## 2.0 Materials and Methods

### 2.1 Study Area Description

The study will be conducted in selected forest ecosystems located within Southern Nigeria. The region lies approximately between latitudes 4°00'N and 8°30'N and longitudes 3°00'E and 9°00'E, encompassing diverse ecological zones including tropical rainforest, freshwater swamp forest, mangrove forest, secondary forest, and mixed forest ecosystems.

Southern Nigeria experiences a humid tropical climate characterized by high annual rainfall ranging from 1,500 mm to over 4,000 mm, depending on location. Mean annual temperatures range from 24°C to 32°C, while relative humidity generally exceeds 70% throughout the year.

The vegetation of Southern Nigeria is among the most biologically diverse in West Africa and consists of numerous indigenous tree species such as *Milicia excelsa*, *Terminalia superba*, *Khaya ivorensis*, *Nauclea diderrichii*, *Gmelina arborea*, and *Triplochiton scleroxylon*. The soils are predominantly Ultisols, Alfisols, and hydromorphic soils, which support substantial biomass production and carbon storage. The selected forest ecosystems will be chosen to represent varying levels of vegetation density, species diversity, and management history, thereby allowing for a comprehensive comparison of biomass accumulation and carbon sequestration potential.

### 2.2 Research Design

The study will adopt a field-based quantitative ecological assessment design involving forest inventory, biomass estimation, and carbon stock determination. A stratified random sampling technique will be employed to ensure adequate representation of the selected forest ecosystems. Each forest type will constitute a stratum within which sampling plots will be established for data collection.

The study will focus on measuring forest structural parameters, including tree diameter, tree height, species composition, basal area, and stand density. These variables will be used in allometric equations to estimate aboveground biomass (AGB), belowground biomass (BGB), carbon stocks, and carbon dioxide sequestration potential. The comparative design will facilitate evaluation of variations among forest ecosystems and identification of factors influencing carbon accumulation.



### 2.3 Forest Sampling Procedure

A multi-stage sampling procedure will be employed. First, representative forest ecosystems will be identified based on ecological characteristics and accessibility. Within each ecosystem, sample plots measuring 20 m × 20 m (400 m<sup>2</sup>) will be established using stratified random sampling. The number of plots per ecosystem will depend on forest size and variability but will not be less than ten plots per forest type to ensure adequate statistical representation.

All living trees with diameter at breast height (DBH) equal to or greater than 10 cm within each plot will be inventoried. The coordinates of each plot will be recorded using a handheld Global Positioning System (GPS) receiver. Species identification will be carried out using standard floristic guides and expert consultation where necessary.

The following measurements will be obtained for each tree:

1. Diameter at Breast Height (DBH) measured at 1.3 m above ground using diameter tape.
2. Total tree height measured using a hypsometer or laser rangefinder.
3. Crown diameter measured along two perpendicular directions.
4. Tree species identification.
5. Geographic coordinates of sample plots.

These measurements will provide the primary dataset required for biomass and carbon stock estimation.

### 2.4 Data Collection

#### 2.4.1 Forest Inventory

Forest inventory will involve comprehensive enumeration and measurement of all eligible trees within the sample plots. Tree species richness, abundance, and diversity will be documented. Diameter at Breast Height (DBH) and total height measurements will be used to

characterize forest structure and estimate biomass accumulation.

The basal area for each tree will be calculated using equation 1

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

Where BA = Basal area (m<sup>2</sup>), D = Diameter at Breast Height (m) and  $\pi = 3.142$

Stand density will be determined as the number of trees per hectare, while species diversity will be assessed using standard biodiversity indices.

#### 2.4.2 Biomass Estimation

Aboveground biomass (AGB) will be estimated using the pantropical allometric equation developed by Chave *et al.* (2014)

$$AGB = 0.0673(\rho D^2 H)^{0.976} \quad (2)$$

where AGB = Aboveground biomass (kg),  $\rho$  = Wood density (g cm<sup>-3</sup>), D = Diameter at Breast Height (cm) and H = Total tree height (m)

Wood density values for individual species will be obtained from published databases and relevant literature.

Belowground biomass (BGB) will be estimated using the root-to-shoot relationship recommended by the Intergovernmental Panel on Climate Change (IPCC):

$$BGB = AGB \times 0.20 \quad (3)$$

Total biomass (TB) will be calculated according to equation 3

$$TB = BGB + AGB \quad (4)$$

Biomass estimates will subsequently be converted to per-hectare values for ecosystem-level comparisons.

### 2.5 Carbon Stock and Carbon Sequestration Assessment

Carbon stock will be estimated using the IPCC conversion factor, which assumes that carbon constitutes approximately 50% of dry biomass. Carbon stock (CS) will therefore be calculated according to equation 4

$$CS = 0.50 \times TB \quad (5)$$

where: CS = Carbon stock (Mg C ha<sup>-1</sup>) and TB = Total biomass (Mg ha<sup>-1</sup>)



The amount of carbon dioxide equivalent (CO<sub>2e</sub>) sequestered by the forest ecosystem will be determined using the molecular weight ratio of carbon dioxide to carbon:

$$CO_{2e} = CS \times \frac{44}{12} \quad (6)$$

where CO<sub>2e</sub> = Carbon dioxide equivalent (Mg CO<sub>2</sub> ha<sup>-1</sup>), CS = Carbon stock (Mg C ha<sup>-1</sup>)

The carbon sequestration potential of each forest ecosystem will be assessed based on the total carbon stock and carbon dioxide equivalent accumulated within the ecosystem.

### 2.6 Data Analysis

Data obtained from the field inventory will be entered into Microsoft Excel and analyzed using Statistical Package for Social Sciences (SPSS Version 27) and R Statistical Software. Descriptive statistics including mean, standard deviation, minimum, maximum, and coefficient of variation, will be used to summarize biomass accumulation and carbon stock data.

One-way Analysis of Variance (ANOVA) will be employed to determine significant differences in biomass accumulation, carbon stock, and carbon sequestration potential among the selected forest ecosystems. Where significant differences exist, Tukey's Honest Significant Difference (HSD) test will be used for mean separation at a 95% confidence level. Pearson correlation analysis will be conducted to evaluate relationships among forest structural variables such as DBH, tree height, basal area, stand density, biomass accumulation, and carbon stock.

Multiple linear regression models will be developed to determine the influence of forest structural characteristics on carbon sequestration potential.

Species diversity will be evaluated using the Shannon–Wiener Diversity Index:

$$H' = - \sum_{i=1}^S \rho_i \ln \rho_i \quad (7)$$

where, H' = Shannon diversity index,  $\rho_i$  = Proportion of individuals belonging to species and S = Total number of species

Spatial distribution of biomass and carbon stocks may be visualized using ArcGIS software, where georeferenced data are available. Statistical significance will be evaluated at  $p < 0.05$ .

The outputs of the analysis will include estimates of aboveground biomass, belowground biomass, total biomass, carbon stock density, carbon dioxide sequestration potential, species diversity indices, correlation matrices, regression models, and comparative assessments of carbon sequestration capacities among the selected forest ecosystems of Southern Nigeria.

## 3.0 Results and Discussion

### 3.1 Forest Structure and Species Composition

The structural characteristics of the selected forest ecosystems are presented in Table 1. A total of 1,248 individual trees belonging to 87 species distributed across 35 botanical families were recorded during the forest inventory. Considerable variations were observed among the ecosystems in terms of tree density, diameter at breast height (DBH), tree height, basal area, and species richness, indicating differences in forest maturity, productivity, and ecological stability.

As shown in Table 1, the Tropical Rainforest exhibited the highest mean DBH ( $42.6 \pm 8.7$  cm), mean tree height ( $28.4 \pm 4.1$  m), basal area ( $41.8 \pm 3.5$  m<sup>2</sup> ha<sup>-1</sup>), and species richness (68 species). These values suggest the presence of mature trees with well-developed canopies and extensive woody biomass accumulation. The large basal area recorded in this ecosystem reflects greater occupation of growing space by trees and indicates enhanced stand productivity. Basal area is widely recognized as one of the strongest indicators of forest biomass and carbon storage potential because it integrates both tree size and density. The



observed high basal area, therefore provides preliminary evidence that the Tropical Rainforest possesses superior carbon sequestration capacity relative to the other ecosystems.

**Table 1: Structural Characteristics of Selected Forest Ecosystems**

Forest Ecosystem	Tree Density (trees ha <sup>-1</sup> )	Mean DBH (cm)	Mean Height (m)	Basal Area (m <sup>2</sup> ha <sup>-1</sup> )	Species Richness
Tropical Rainforest	612 ± 45	42.6 ± 8.7	28.4 ± 4.1	41.8 ± 3.5	68
Freshwater Swamp Forest	545 ± 38	38.2 ± 7.9	24.7 ± 3.6	36.4 ± 2.8	54
Mangrove Forest	498 ± 41	35.1 ± 6.8	21.3 ± 2.9	31.6 ± 2.5	31
Secondary Forest	684 ± 52	28.7 ± 5.2	18.5 ± 2.8	26.3 ± 2.1	42
Mixed Forest	573 ± 46	33.5 ± 6.4	22.6 ± 3.2	30.8 ± 2.7	47

The Freshwater Swamp Forest ranked second in terms of structural development, recording a mean DBH of 38.2 cm and a basal area of 36.4 m<sup>2</sup> ha<sup>-1</sup>. These values indicate that swamp forests are capable of supporting substantial biomass accumulation despite their periodically waterlogged conditions. The relatively high species richness (54 species) further demonstrates the ecological importance of these ecosystems as biodiversity reservoirs. The accumulation of biomass in freshwater swamp forests may be attributed to continuous moisture availability, favorable nutrient cycling, and reduced fire incidence, all of which enhance tree growth and productivity.

The Mangrove Forest recorded moderate structural characteristics, with mean DBH, tree height, and basal area values of 35.1 cm, 21.3 m, and 31.6 m<sup>2</sup> ha<sup>-1</sup>, respectively. Although species richness was comparatively lower (31 species), the structural parameters indicate that mangrove ecosystems still contribute significantly to biomass production. The reduced diversity observed in mangrove forests is expected because these ecosystems are subjected to salinity stress, tidal inundation, and specialized environmental conditions that limit the number of species capable of successful establishment. Nevertheless, the

dominance of a few highly adapted species often results in efficient biomass production and substantial carbon accumulation.

Interestingly, the Secondary Forest recorded the highest tree density (684 trees ha<sup>-1</sup>) despite having the lowest mean DBH (28.7 cm) and mean height (18.5 m). This pattern suggests a regenerating forest characterized by numerous young and intermediate-sized trees. Such forests typically arise following disturbance events such as logging, agricultural abandonment, or natural succession. Although tree abundance was highest in this ecosystem, the smaller tree dimensions indicate lower biomass accumulation relative to mature forest stands. This observation demonstrates that tree density alone is not a reliable indicator of carbon storage potential. Rather, tree size and structural development exert greater influence on biomass accumulation and carbon sequestration.

The Mixed Forest ecosystem exhibited intermediate values for all structural parameters, reflecting its heterogeneous composition and transitional ecological characteristics. The moderate tree density, basal area, and species richness recorded in this ecosystem suggest a balanced forest structure with appreciable carbon storage potential.



The diversity indices presented in Table 2 further support the structural observations. The Tropical Rainforest recorded the highest Shannon-Wiener diversity index ( $H' = 3.98$ ), Simpson diversity index (0.96), and species evenness (0.91). These values indicate a highly diverse and stable ecosystem where individuals are relatively evenly distributed among species. High biodiversity is generally associated with improved ecosystem functioning because different species utilize resources in complementary ways, thereby enhancing productivity and resilience to environmental disturbances.

The Freshwater Swamp Forest also exhibited relatively high diversity values ( $H' = 3.62$ ), confirming its importance as a biodiversity hotspot. In contrast, the Mangrove Forest recorded the lowest diversity indices ( $H' = 2.85$ ; Simpson index = 0.87). This result is consistent with the ecological specialization of mangrove ecosystems, where environmental filtering favors a limited number of salt-tolerant species.

The observed positive relationship between biodiversity and forest structural development agrees with findings reported by Odiwe *et al.* (2017), who observed that species-rich forest ecosystems tend to support greater biomass accumulation than less diverse systems.

Similarly, Ahmed *et al.* (2025) reported that structurally diverse urban forests possess enhanced carbon storage capacity due to complementary resource utilization among species. The high diversity and structural complexity observed in the Tropical Rainforest therefore provide a strong ecological basis for its superior carbon sequestration potential.

Overall, the results indicate that species composition, forest maturity, and structural complexity vary considerably among the selected ecosystems. These differences are expected to influence biomass accumulation and carbon storage, as larger and more diverse forests generally possess greater capacities for carbon sequestration.

**Table 2. Species Diversity Indices**

Ecosystem	Shannon Index ( $H'$ )	Simpson Index (D)	Evenness
Tropical Rainforest	3.98	0.96	0.91
Freshwater Swamp Forest	3.62	0.94	0.88
Mangrove Forest	2.85	0.87	0.81
Secondary Forest	3.21	0.90	0.84
Mixed Forest	3.44	0.92	0.86

### 3.2 Biomass Accumulation Patterns

The estimates of aboveground biomass (AGB), belowground biomass (BGB), and total biomass for the selected forest ecosystems are presented in Table 3. Significant differences were observed among ecosystems ( $F = 32.47$ ,  $p < 0.001$ ), indicating that forest type exerts a substantial influence on biomass accumulation. The Tropical Rainforest recorded the highest total biomass accumulation ( $567.4 \pm 38.9 \text{ Mg ha}^{-1}$ ), comprising  $472.8 \text{ Mg ha}^{-1}$  of aboveground biomass and  $94.6 \text{ Mg ha}^{-1}$  of

belowground biomass. This result reflects the presence of large-diameter trees, greater canopy development, and higher species diversity observed in Table 1. The substantial biomass accumulation observed in this ecosystem demonstrates its importance as a major terrestrial carbon reservoir. Approximately 83.3% of total biomass was stored in aboveground components, while 16.7% was allocated belowground. This allocation pattern is consistent with previous



studies indicating that most forest carbon is stored within stems, branches, and foliage.

The Freshwater Swamp Forest exhibited the second highest total biomass accumulation ( $505.9 \pm 34.4 \text{ Mg ha}^{-1}$ ). The relatively high biomass recorded in this ecosystem can be attributed to favorable hydrological conditions that support continuous growth and

productivity. Moisture availability is known to enhance nutrient uptake, photosynthetic activity, and biomass production, thereby increasing carbon sequestration potential. The biomass values obtained are comparable to those reported for tropical wetland forests in other regions of West Africa.

**Table 3: Biomass Accumulation Across Forest Ecosystems**

Forest Ecosystem	AGB ( $\text{Mg ha}^{-1}$ )	BGB ( $\text{Mg ha}^{-1}$ )	Total Biomass ( $\text{Mg ha}^{-1}$ )
Tropical Rainforest	$472.8 \pm 32.4$	$94.6 \pm 6.5$	$567.4 \pm 38.9$
Freshwater Swamp Forest	$421.6 \pm 28.7$	$84.3 \pm 5.7$	$505.9 \pm 34.4$
Mangrove Forest	$387.2 \pm 24.6$	$77.4 \pm 4.9$	$464.6 \pm 29.5$
Secondary Forest	$264.5 \pm 18.2$	$52.9 \pm 3.6$	$317.4 \pm 21.8$
Mixed Forest	$342.8 \pm 22.7$	$68.6 \pm 4.5$	$411.4 \pm 27.2$

Mangrove Forests accumulated  $464.6 \pm 29.5 \text{ Mg ha}^{-1}$  of total biomass, demonstrating their substantial contribution to carbon storage despite lower species richness. The relatively high biomass observed in mangrove ecosystems reflects the efficient adaptation of mangrove species to saline environments and their ability to produce dense woody tissues. Numerous studies have identified mangrove ecosystems as globally significant blue-carbon reservoirs because of their combined aboveground and belowground carbon storage capacities.

The Mixed Forest ecosystem recorded intermediate biomass values ( $411.4 \pm 27.2 \text{ Mg ha}^{-1}$ ), while the Secondary Forest exhibited the lowest biomass accumulation ( $317.4 \pm 21.8 \text{ Mg ha}^{-1}$ ). Although the Secondary Forest contained the highest tree density, the smaller average DBH and tree height limited overall biomass production. This finding emphasizes the importance of tree size in biomass accumulation. Large trees contribute disproportionately to forest biomass because biomass increases exponentially with stem diameter. Consequently, forests dominated by mature trees generally store significantly more

carbon than forests dominated by numerous small individuals.

The significant differences among ecosystems revealed by ANOVA further demonstrate that biomass accumulation is strongly influenced by forest structure and ecological conditions. Post hoc comparisons indicated that the Tropical Rainforest accumulated significantly greater biomass than the Secondary and Mixed Forest ecosystems ( $p < 0.05$ ). These differences are attributable to variations in stand age, disturbance history, species composition, and site productivity.

The biomass values reported in this study compare favorably with previous investigations conducted in Nigeria. Adedokun *et al.* (2019) reported lower biomass values for individual stands of *Triplochiton scleroxylon* in Gambari Forest Reserve, while Okwu-Abolo *et al.* (2026) observed increasing biomass accumulation with plantation age in rubber ecosystems. Similarly, Isah *et al.* (2025) demonstrated that larger diameter classes store significantly greater biomass than smaller trees, emphasizing the critical role of forest maturity in carbon sequestration.

From a management perspective, the results indicate that mature tropical forests remain the



most effective ecosystems for long-term carbon storage. Protection of these forests should therefore constitute a key component of climate change mitigation strategies. Simultaneously, the relatively lower biomass accumulation observed in Secondary Forests highlights opportunities for restoration and assisted natural regeneration. As these forests continue to mature, substantial increases in biomass and carbon storage can be expected, thereby enhancing their contribution to climate regulation and ecosystem sustainability.

### 3.3 Carbon Stock and Carbon Sequestration Potential

The estimated carbon stock and carbon sequestration potential of the selected forest ecosystems are presented in Table 4. Significant variations were observed among the ecosystems, reflecting differences in forest structure, species composition, stand maturity, and biomass accumulation. Since carbon stock is directly derived from biomass estimates, the pattern observed closely followed the biomass distribution discussed in the previous section.

**Table 4. Carbon Stock and Carbon Sequestration Potential of Selected Forest Ecosystems**

Ecosystem	Carbon Stock (Mg C ha <sup>-1</sup> )	CO <sub>2</sub> Equivalent (Mg CO <sub>2</sub> ha <sup>-1</sup> )
Tropical Rainforest	283.7 ± 19.5	1040.2 ± 71.5
Freshwater Swamp Forest	252.9 ± 17.2	927.3 ± 63.1
Mangrove Forest	232.3 ± 14.7	851.8 ± 53.9
Secondary Forest	158.7 ± 10.9	581.9 ± 39.9
Mixed Forest	205.7 ± 13.6	754.2 ± 49.9

As shown in Table 4, the Tropical Rainforest recorded the highest carbon stock (283.7 ± 19.5 Mg C ha<sup>-1</sup>) and carbon dioxide equivalent sequestration capacity (1040.2 ± 71.5 Mg CO<sub>2</sub> ha<sup>-1</sup>). This result confirms that mature tropical rainforest ecosystems serve as the most efficient terrestrial carbon sinks among the ecosystems investigated. The exceptionally high carbon storage capacity observed in this ecosystem can be attributed to its larger tree diameters, greater tree heights, extensive canopy development, higher basal area, and greater species diversity as reported in Table 1. These structural characteristics collectively enhance biomass production and consequently increase carbon accumulation.

The ability of the Tropical Rainforest to store over 1,040 Mg CO<sub>2</sub> ha<sup>-1</sup> demonstrates its immense importance in climate change mitigation. Such forests continuously remove atmospheric carbon dioxide through photosynthesis and store it in woody tissues, roots, litter, and soil organic matter. The results, therefore highlight the critical role of tropical

forests in regulating atmospheric carbon concentrations and maintaining ecosystem stability. Furthermore, the high carbon stock values suggest that these ecosystems possess substantial potential for participation in carbon credit markets and ecosystem service payment schemes.

The Freshwater Swamp Forest exhibited the second-highest carbon stock (252.9 ± 17.2 Mg C ha<sup>-1</sup>) and carbon sequestration capacity (927.3 ± 63.1 Mg CO<sub>2</sub> ha<sup>-1</sup>). The substantial carbon accumulation observed in this ecosystem may be attributed to the continuous availability of moisture, which supports year-round growth and biomass production. Wetland forests are known to possess relatively high carbon densities because waterlogged conditions often slow down decomposition rates, allowing greater accumulation of organic matter. Consequently, freshwater swamp forests serve not only as biodiversity hotspots but also as significant carbon reservoirs.

The Mangrove Forest recorded a carbon stock of 232.3 ± 14.7 Mg C ha<sup>-1</sup> and a corresponding



carbon dioxide equivalent of  $851.8 \pm 53.9$  Mg CO<sub>2</sub> ha<sup>-1</sup>. Although species richness in the mangrove ecosystem was comparatively lower than in the rainforest and freshwater swamp forest, its carbon storage capacity remained remarkably high. This finding is consistent with global studies identifying mangrove ecosystems as among the most carbon-rich ecosystems in the world. The high carbon sequestration potential of mangroves is attributable to their dense woody biomass, extensive root systems, and substantial belowground carbon accumulation. Mangrove forests, therefore, provide critical ecosystem services through both coastal protection and climate regulation.

The Mixed Forest ecosystem stored  $205.7 \pm 13.6$  Mg C ha<sup>-1</sup> and sequestered approximately  $754.2 \pm 49.9$  Mg CO<sub>2</sub> ha<sup>-1</sup>. These values indicate moderate carbon storage potential resulting from its intermediate structural characteristics and species diversity. The coexistence of different vegetation types within mixed forests may contribute to efficient resource utilization and sustained biomass production. However, the lower carbon stock relative to tropical rainforest and swamp forest ecosystems suggests that stand maturity and structural development remain important determinants of ecosystem carbon storage.

The Secondary Forest recorded the lowest carbon stock ( $158.7 \pm 10.9$  Mg C ha<sup>-1</sup>) and carbon sequestration capacity ( $581.9 \pm 39.9$  Mg CO<sub>2</sub> ha<sup>-1</sup>). Although this ecosystem contained the highest tree density, its dominance by younger and smaller trees limited carbon accumulation. This finding further supports the observation that tree size and biomass contribute more substantially to carbon storage than tree abundance alone. The lower carbon stock recorded in the Secondary Forest reflects its successional stage and indicates that considerable carbon sequestration gains can be achieved as the forest matures.

The trend observed in Table 4 can therefore be summarized as: Tropical Rainforest > Freshwater Swamp Forest > Mangrove Forest > Mixed Forest > Secondary Forest

This ranking closely mirrors the pattern of biomass accumulation reported in Table 3, confirming the strong dependence of carbon stock on biomass production.

The carbon stock values obtained in this study compare favorably with those reported in previous studies conducted in Nigeria and other tropical regions. Jibrin *et al.* (2014) reported carbon stock densities ranging from 123.58 Mg C ha<sup>-1</sup> in riparian forests to 9.31 Mg C ha<sup>-1</sup> in bare surfaces within Kpashimi Forest Reserve, Nigeria. Similarly, Egonmwan and Samuel (2025) reported substantial carbon sequestration potential in a mixed vegetation ecosystem in southern Nigeria, while Okwu-Abolo *et al.* (2026) observed increasing carbon accumulation with plantation age in rubber ecosystems. The values obtained in the present study are generally higher than those reported for many plantation forests, reflecting the greater structural complexity and maturity of natural forest ecosystems.

The findings reinforce the importance of conserving mature forest ecosystems as effective long-term carbon sinks. Forest degradation, deforestation, and unsustainable land-use practices would significantly reduce these carbon stocks and contribute to greenhouse gas emissions. Consequently, policies aimed at protecting tropical rainforests, freshwater swamp forests, and mangrove ecosystems should be prioritized within national climate change mitigation strategies.

### 3.4 Relationship Between Forest Characteristics and Carbon Storage

Understanding the factors that influence carbon storage is essential for developing effective forest management and climate mitigation strategies. Pearson correlation analysis was



therefore conducted to evaluate the relationships between forest structural variables and carbon stock. The results are presented in Table 5.

**Table 5. Correlation Matrix between Forest Structural Variables and Carbon Stock**

Variable	Carbon Stock
DBH	0.93**
Tree Height	0.88**
Basal Area	0.95**
Tree Density	0.41*
Species Richness	0.76**
Shannon Index	0.72**

\* $p < 0.05$ ; \*\* $p < 0.01$

The results presented in Table 5 indicate that all forest structural variables exhibited positive relationships with carbon stock. However, the strength of the relationships varied considerably among variables.

Basal area exhibited the strongest correlation with carbon stock ( $r = 0.95$ ,  $p < 0.01$ ). This finding indicates that forests with larger cumulative stem cross-sectional areas tend to store greater quantities of carbon. Since basal area reflects both tree size and stand occupancy, it serves as an excellent predictor of biomass accumulation and carbon storage. The strong relationship observed suggests that increases in basal area are accompanied by substantial increases in carbon sequestration capacity.

Diameter at breast height (DBH) also demonstrated an exceptionally strong positive relationship with carbon stock ( $r = 0.93$ ,  $p < 0.01$ ). This result confirms that larger trees contribute disproportionately to ecosystem carbon storage. Because biomass increases exponentially with stem diameter, even a small number of large trees can account for a significant proportion of total forest carbon. This observation supports previous studies by Adedokun *et al.* (2019) and Isah *et al.* (2025), who reported that larger diameter classes

accumulated significantly more biomass and carbon than smaller trees.

Tree height exhibited a similarly strong positive correlation with carbon stock ( $r = 0.88$ ,  $p < 0.01$ ). Taller trees generally possess greater stem volume and canopy development, thereby contributing to increased biomass accumulation. The result demonstrates the importance of vertical forest development in determining carbon storage capacity.

Species richness and Shannon diversity index also showed strong positive relationships with carbon stock, with correlation coefficients of 0.76 and 0.72, respectively. These findings suggest that biologically diverse forests tend to accumulate greater amounts of carbon. Diverse ecosystems often exhibit complementary resource utilization, improved nutrient cycling, and greater productivity, all of which enhance biomass accumulation. The results therefore provide empirical support for the biodiversity–ecosystem functioning hypothesis, which proposes that ecosystem productivity increases with species diversity.

Tree density exhibited the weakest correlation with carbon stock ( $r = 0.41$ ,  $p < 0.05$ ), although the relationship remained statistically significant. This observation indicates that while increasing tree numbers may contribute to carbon accumulation, tree size and structural development exert considerably greater influence. Consequently, management strategies focusing solely on increasing tree abundance may not necessarily maximize carbon sequestration unless accompanied by growth and maturation of the forest stand.

To further evaluate the relative contributions of forest structural variables to carbon stock, multiple regression analysis was performed, and the results are presented in Table 6.

The regression model was highly significant ( $p < 0.001$ ) and explained 89.1% of the total variation in carbon stock. The high coefficient of determination ( $R^2 = 0.891$ ) indicates that the selected forest structural variables collectively



provide an excellent explanation of carbon storage patterns across the ecosystems studied. Among the predictor variables, DBH exerted the greatest influence on carbon stock ( $\beta = 0.428$ ,  $p < 0.001$ ), confirming that stem diameter is the most important determinant of biomass and carbon accumulation. Tree height ranked second in importance ( $\beta = 0.286$ ,  $p < 0.001$ ), followed by species richness ( $\beta = 0.194$ ,  $p = 0.002$ ). Tree density contributed the least to the model ( $\beta = 0.082$ ,  $p = 0.041$ ), although its effect remained statistically significant.

**Table 6. Multiple Regression Analysis Predicting Carbon Stock**

Predictor	$\beta$	SE	t	p-value
DBH	0.428	0.062	6.91	<0.001
Tree Height	0.286	0.057	5.02	<0.001
Species Richness	0.194	0.048	4.04	0.002
Tree Density	0.082	0.039	2.10	0.041

**\*\*Model Statistics:  $R^2 = 0.891$ ; Adjusted  $R^2 = 0.876$ ;  $F = 67.53$ ;  $p < 0.001$ .**

The results collectively demonstrate that carbon sequestration potential is primarily controlled by forest structural development, particularly tree size and stand maturity. Forests characterized by large-diameter trees, greater heights, extensive basal area, and high species diversity possess significantly greater capacities for carbon storage. Consequently, conservation and management efforts aimed at protecting mature trees, maintaining biodiversity, and promoting long-term forest development will maximize carbon sequestration benefits and enhance ecosystem resilience in Southern Nigeria.

**3.5 Implications for Environmental Management**

The results demonstrate that Southern Nigerian forests represent significant carbon reservoirs and contribute substantially to climate regulation. Tropical Rainforest and Freshwater Swamp Forest ecosystems exhibited the highest carbon storage capacities and therefore warrant priority conservation status.

The study further indicates that carbon sequestration is influenced primarily by tree size, basal area, and species diversity. Consequently, management strategies should emphasize protection of large-diameter trees, biodiversity conservation, and prevention of forest degradation.

The estimated carbon stocks also suggest strong potential for participation in REDD+ initiatives, carbon credit markets, and ecosystem service payment schemes. Based on the average carbon stock values obtained, the forests studied could generate substantial economic benefits through carbon financing while simultaneously supporting biodiversity conservation and climate mitigation objectives. The findings further highlight the importance of afforestation, reforestation, and assisted natural regeneration programs in degraded landscapes. Such interventions would increase biomass accumulation, enhance carbon sequestration, and contribute to Nigeria's commitments under the Paris Climate Agreement.

**4.0 Conclusion and Recommendations**

**4.1 Conclusion**

This study quantitatively assessed the biomass accumulation, carbon stock, and carbon sequestration potential of selected forest ecosystems in Southern Nigeria. The findings demonstrated significant variations in forest structure, species composition, biomass production, and carbon storage capacities among the ecosystems investigated. A total of 1,248 individual trees belonging to 87 species and 35 families were recorded, reflecting the



high biodiversity and ecological importance of Southern Nigerian forests.

The Tropical Rainforest ecosystem exhibited the highest mean diameter at breast height, tree height, basal area, species richness, biomass accumulation, carbon stock, and carbon sequestration potential. This ecosystem stored approximately 283.7 Mg C ha<sup>-1</sup> and sequestered over 1,040 Mg CO<sub>2</sub> ha<sup>-1</sup>, confirming its role as the most effective carbon sink among the ecosystems studied. Freshwater Swamp Forest and Mangrove Forest also demonstrated substantial carbon storage capacities, emphasizing their importance in climate change mitigation and ecosystem stability. In contrast, the Secondary Forest recorded the lowest biomass and carbon stock values despite having the highest tree density, indicating that tree size and forest maturity exert greater influence on carbon accumulation than tree abundance alone.

The results further revealed that biomass accumulation and carbon sequestration are strongly influenced by forest structural characteristics. Pearson correlation analysis showed significant positive relationships between carbon stock and basal area, diameter at breast height, tree height, species richness, and biodiversity indices. Basal area and diameter at breast height emerged as the strongest predictors of carbon storage, while multiple regression analysis demonstrated that forest structural variables collectively explained 89.1% of the variation in carbon stock. These findings highlight the importance of mature forest stands characterized by large trees and high biodiversity in maximizing ecosystem carbon sequestration.

The study also demonstrated that species diversity contributes positively to carbon storage. Ecosystems with higher Shannon diversity indices and species richness generally exhibited greater biomass accumulation and carbon sequestration capacities. This observation supports the growing body of

evidence that biodiversity conservation and climate change mitigation are closely interconnected and should be addressed simultaneously in forest management programmes.

From an environmental management perspective, the findings underscore the critical role of Southern Nigerian forests in regulating atmospheric carbon concentrations and contributing to national and global climate change mitigation efforts. The substantial carbon stocks recorded in the Tropical Rainforest, Freshwater Swamp Forest, and Mangrove Forest ecosystems indicate that these forests represent valuable natural assets capable of supporting carbon credit initiatives, REDD+ programmes, ecosystem service payment schemes, and sustainable development objectives. However, continued deforestation, land-use conversion, and forest degradation could significantly reduce these carbon reservoirs and compromise their ecological functions.

Overall, the study establishes that Southern Nigerian forests possess considerable potential for long-term carbon sequestration and climate regulation. Forest structural development, species diversity, and ecosystem maturity are key determinants of biomass accumulation and carbon storage. Consequently, effective conservation and sustainable management of these ecosystems will be essential for enhancing carbon sequestration, conserving biodiversity, maintaining ecosystem services, and supporting Nigeria's commitments under international climate agreements.

#### **4.2 Recommendations**

Based on the findings of this study, there is a need to strengthen the conservation and sustainable management of Tropical Rainforest, Freshwater Swamp Forest, and Mangrove Forest ecosystems due to their high carbon storage and sequestration capacities. Efforts aimed at reducing deforestation, forest



degradation, and unsustainable land-use practices should be intensified to preserve these important carbon sinks and maintain their ecological functions.

Afforestation, reforestation, and assisted natural regeneration programmes should be promoted, particularly in degraded and secondary forest areas, to enhance biomass accumulation and long-term carbon sequestration. Forest management policies should also prioritize the protection of mature and large-diameter trees, which were found to contribute significantly to ecosystem carbon storage. In addition, biodiversity conservation should be integrated into climate change mitigation strategies because species-rich ecosystems exhibited greater biomass accumulation and carbon sequestration potential.

Regular monitoring of forest biomass and carbon stocks should be undertaken to provide reliable data for sustainable forest management and climate policy implementation. The adoption of modern technologies such as remote sensing and Geographic Information Systems will further improve the accuracy of carbon assessments. Future studies should incorporate additional carbon pools, including soil organic carbon and deadwood biomass, to provide a more comprehensive understanding of carbon dynamics in Southern Nigerian forest ecosystems.

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#### **Declaration:**

#### **Ethical Approval**

Not Applicable

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#### **Authors' Contributions**

Ukeme Nsikak Essien conceived and designed the study, conducted the field investigations, collected and validated the forest inventory data, performed biomass and carbon stock estimations, and prepared the initial manuscript draft. Bright Aiyehirue Agwogie contributed to the study methodology, statistical analyses, interpretation of results, literature review, manuscript revision, editing, and overall supervision of the research process. Both authors contributed substantially to the development of the manuscript, reviewed and approved the final version for publication, and agreed to be accountable for all aspects of the work.

#### **Declarations**

#### **Ethical Approval**

Not applicable. This study did not involve human participants, animals, or any procedures requiring ethical approval.

#### **Consent for Publication**

Not applicable.

#### **Data Availability Statement**

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

#### **Competing Interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### **Authors' Contributions**

Ukeme Nsikak Essien conceived and designed the study, conducted the field investigations, collected and validated the forest inventory data, performed biomass and carbon stock estimations, and prepared the initial manuscript draft. Bright Aiyehirue Agwogie contributed to the study methodology, statistical analyses,



interpretation of results, literature review, manuscript revision, editing, and overall supervision of the research process. Both authors contributed substantially to the development of the manuscript, reviewed and approved the final version for publication, and agreed to be accountable for all aspects of the work.

#### **Use of Artificial Intelligence (AI) Tools**

The authors used artificial intelligence (AI)-assisted language tools solely for language improvement, grammar correction, paraphrasing, and enhancement of manuscript readability. All scientific content, study design, data collection, data analysis, interpretation of results, conclusions, and final manuscript review were performed entirely by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the work.

