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ORIGINAL RESEARCH ARTICLE

Estimation and Mapping of Above and Below Ground Biomass Distribution in Southern Guinea Savannah Zone of Taraba State, Nigeria

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ABSTRACT

This study assessed temporal and spatial variations in above- and below-ground biomass (AGB and BGB) in the Southern Guinea Savannah of Taraba State, Nigeria, from 1987 to 2024 using multi-temporal Landsat data, Normalized Difference Vegetation Index (NDVI) modeling, and soil organic carbon (SOC) analysis. AGB was derived from NDVI-based regression equations, while BGB was estimated using SOC as a proxy following the modified approach. Results show a marked decline in vegetation productivity and carbon storage over the 37-year period. AGB ranged from 0–84.82 t ha^{-1} (1987) to 0–95.20 t ha^{-1} (2024), with low-biomass zones expanding from 36.8 % to > 60 % of the landscape. Mean biomass peaked at 39.79 t ha^{-1} in 2014 before falling to 32.39 t ha^{-1} in 2024, indicating renewed degradation after a brief recovery phase. SOC values varied from 0.36–12.2 g kg^{-1}, highest in forest and riparian sites, confirming strong vegetation–soil carbon coupling. ANOVA results ($F = 49.129$, $p < 0.001$) revealed significant inter-year differences, and Tukey's HSD indicated a major decline between 2014 and 2024 ($p < 0.001$). The NDVI–AGB correlation weakened progressively ($R^2 = 0.958 \rightarrow 0.743$), reflecting landscape fragmentation and ecosystem instability. Overall, total ecosystem biomass decreased by over 40 %, demonstrating severe loss of carbon sequestration capacity. These findings highlight the transition of the Southern Guinea Savannah toward a degraded ecological state and emphasize the urgency of community-based reforestation, assisted natural regeneration, and the integration of biomass–carbon monitoring into Nigeria's climate-adaptation and land-restoration policies.

Introduction

Biomass estimation plays a central role in understanding terrestrial carbon dynamics, ecosystem productivity, and the response of landscapes to anthropogenic and climatic pressures. In tropical savannah ecosystems, where vegetation structure exhibits marked spatial and temporal variability, accurate estimation and mapping of both above-ground biomass (AGB) and below-ground biomass (BGB) are critical for assessing ecosystem services, especially carbon sequestration and climate regulation (Henry et al., 2011; Wu, De Pauw, & Helldén, 2013). The African Guinea Savannah zone; an extensive ecological belt spanning West and Central Africa represents one of the most dynamic landscapes, where agricultural expansion, grazing, fuelwood extraction, and urbanization continuously alter vegetation cover and biomass distribution (Grace et al., 2006; Chapungu, Nhamo, & Gatti, 2020).

In Nigeria, the Guinea Savannah occupies a large proportion of the country's landmass and supports substantial agricultural and forestry activities. The Southern Guinea Savannah (SGS) agro-ecological zone of Taraba State, in particular, serves as a vital socio-ecological interface, providing food, energy, and livelihood resources for rural communities while also functioning as a significant carbon reservoir (Jibrin, Jaiyeoba, Oladipo, & Kim, 2018). However, decades of deforestation, overgrazing, and shifting cultivation have led to widespread vegetation degradation and loss of biomass, threatening both ecological integrity and the sustainability of local livelihoods (Oruonye & Abbas, 2011).

Above-ground biomass estimation has been widely used as a proxy for assessing ecosystem carbon stocks, forest degradation, and land-use change (Avitabile et al., 2016; Cánovas-García et al, 2015). While several studies have quantified AGB across forested and savannah ecosystems in Nigeria, below-ground biomass representing root systems and soil organic matter remains underexplored despite its substantial contribution to total carbon storage (Salako & Tian, 2004; Henry et al., 2011). BGB can account for 20–40% of total ecosystem biomass in savannah landscapes (Mokany, Raison, & Prokushkin, 2006), yet it is often excluded from regional carbon accounting due to methodological difficulties and data scarcity.

The integration of field-based allometric equations with remote sensing and GIS techniques has significantly improved biomass estimation and mapping accuracy at landscape scales (Liu et al., 2024; Chapungu et al., 2020). Remotely sensed indices, such as NDVI and EVI derived from Landsat or Sentinel imagery, have proven effective in detecting vegetation structure and productivity gradients across savannah mosaics (Liu et al., 2024). However, in the Southern Guinea Savannah of Nigeria, few studies have combined multi-temporal remote sensing data with field biomass measurements to evaluate long-term spatial and temporal variations in both AGB and BGB. Consequently, the absence of comprehensive biomass distribution maps constrains the ability of policymakers and conservation planners to monitor land degradation, estimate carbon fluxes, and design climate adaptation strategies.

Despite increasing attention to biomass estimation in tropical regions, the Southern Guinea Savannah zone of Taraba State remains poorly characterized in terms of its spatio-temporal biomass dynamics. Existing studies have largely focused on above-ground vegetation assessments without incorporating below-ground components or evaluating the cumulative implications of biomass decline on ecosystem services (Jibrin et al., 2018; Salako & Tian, 2004). This knowledge gap limits understanding of carbon stock variability, soil fertility, and the ecological resilience of the agro-ecosystem. Mapping both AGB and BGB at high spatial resolution is therefore crucial for developing sustainable land-use strategies, monitoring deforestation trends, and informing Nigeria's commitments under global climate frameworks such as REDD+ and the Paris Agreement.

This study aims to estimate and map the spatial and temporal distribution of above- and below-ground biomass in the Southern

Guinea Savannah agro-ecological zone of Taraba State, Nigeria. Specifically, the objectives are to:

i. Estimate the spatial variation of AGB and BGB across different land-use and vegetation types using multi-temporal remote sensing data and allometric models.
ii. Map the changes in biomass distribution between 1987 and 2024 to assess trends in vegetation degradation and recovery.
iii. Evaluate the ecological and climatic implications of biomass decline for carbon sequestration and ecosystem service sustainability.

The study hypothesizes that:

- (H_1) Above- and below-ground biomass in the Southern Guinea Savannah zone have significantly declined over the past three decades due to increasing anthropogenic pressures; and
- (H_2) Areas of high biomass concentration are spatially associated with less disturbed forests and riparian zones, indicating the persistence of ecological strongholds.

Through this approach, the study provides essential baseline information for land management, carbon accounting, and climate resilience planning in Nigeria's savannah ecosystems.

Materials and Methods

Study Area

The study was conducted within the Southern Guinea Savannah agro-ecological zone of Taraba State, Nigeria, located approximately between latitudes 6°30′N and 8°30′N of the equator and longitudes 10°00′E and 11°30′E of the Prime Meridian (Fig. 1). The region represents a transitional ecological zone between the forest belt of southern Nigeria and the Sudan Savannah to the north. It is characterized by a tropical wet-and-dry climate, with annual rainfall ranging from 1,000 mm to 1,500 mm and mean annual temperatures of 26–32 °C (Oruonye & Abbas, 2011).

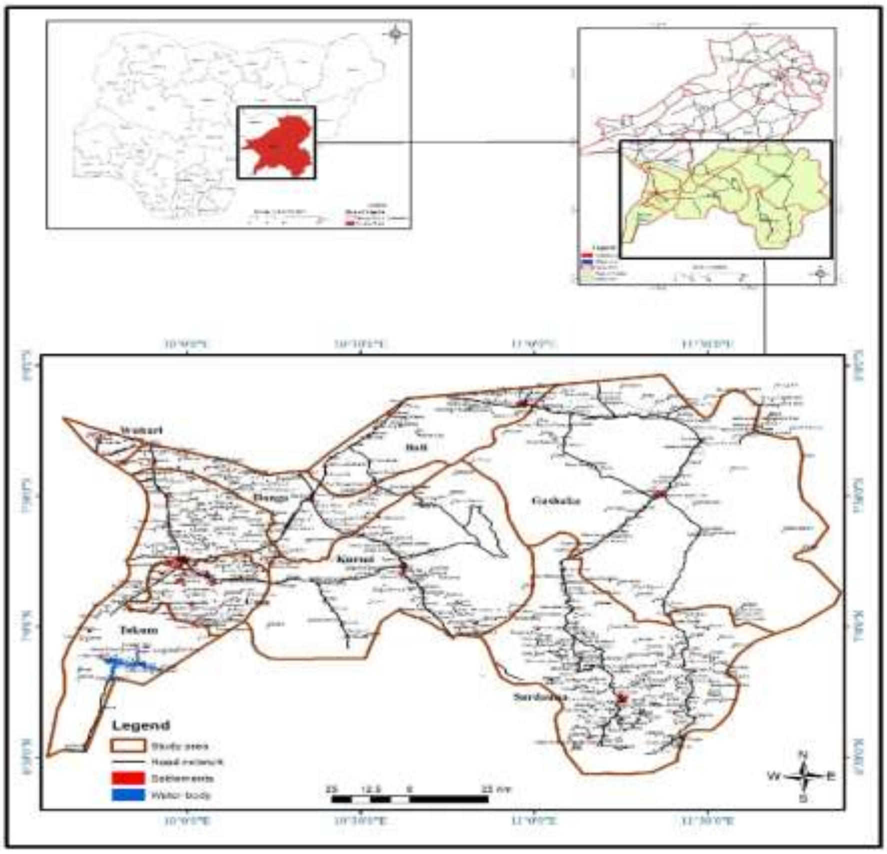

Figure 1: The Study Area

Topographically, the area lies on undulating plains that gradually rise eastward toward the Mambilla Plateau, with elevations between 200 m and 1,000 m above sea level. The soils are largely ferruginous tropical soils and lithosols, developed from crystalline basement rocks and volcanic materials, and are moderately fertile but susceptible to erosion and compaction (Oruonye & Abbas, 2011). The natural vegetation is a mosaic of wooded savannah, shrubland, and grassland, interspersed with gallery forests along river valleys. However, decades of deforestation, agricultural expansion, fuelwood harvesting, and overgrazing have led to widespread land degradation and decline in vegetation biomass (Jibrin et al., 2018). The Southern Guinea Savannah zone thus provides an ideal landscape for evaluating biomass loss and its ecological implications.

Data Sources and Acquisition

This study employed a multi-temporal remote sensing and geospatial analysis framework to estimate and map above- and below-ground biomass (AGB and BGB) across the Southern Guinea Savannah agro-ecological zone of Taraba State, Nigeria, between 1987 and 2024. Multi-date Landsat images (TM, ETM+, and OLI) were retrieved from the United States Geological Survey (USGS) Earth Explorer for the years 1987, 2004, 2014, and 2024. Image selection focused on the late dry to early wet season (March–May) to minimize cloud contamination and ensure consistent vegetation greenness across years.

All imagery had a 30 m spatial resolution and underwent preprocessing to correct atmospheric, radiometric, and geometric distortions. Atmospheric correction was implemented using the Dark Object

Subtraction (DOS1) method, and all datasets were projected to the UTM Zone 32N (WGS-84 datum) to ensure spatial consistency. The study area was delineated using administrative shapefiles of Taraba State obtained from the National Space Research and Development Agency (NASRDA).

Above-Ground Biomass (AGB) Estimation

Above-ground biomass was estimated from Landsat-derived Normalized Difference Vegetation Index (NDVI) values, computed using the standard equation:

$$NDVI = (NIR - RED) / (NIR + RED) \qquad (1)$$

where NIR and RED denote the near-infrared and red spectral bands, respectively.

A regression model linking NDVI to field or literature-based biomass data was employed following established models for West African savannahs (Henry et al., 2011; Chapungu, Nhamo, & Gatti, 2020; Avitabile et al., 2016):

$$AGB = a * e^{(b * NDVI)} \qquad (2)$$

where a and b are empirically derived coefficients calibrated for tropical savannah vegetation.

The resulting AGB maps were classified into four categories reflecting biomass density gradients:

- Low biomass: 0–35.10 t ha^{-1}
- Moderate biomass: 35.10–50.87 t ha^{-1}
- High biomass: 50.87–67.04 t ha^{-1}
- Very high biomass: >67.04 t ha^{-1}

Change detection was conducted using raster overlay and zonal statistics in ArcGIS 10.8 to quantify spatio-temporal shifts in biomass between 1987–2024.

Below-Ground Biomass (BGB) Estimation Using Soil Organic Carbon

Below-ground biomass was estimated indirectly using soil organic carbon (SOC) as a proxy, given its strong correlation with root biomass in tropical savannah soils (Mokany, Raison, & Prokushkin, 2006; Salako & Tian, 2004).

Soil samples were collected from ten representative vegetation and land-use categories, including woodland, shrub savannah, grassland, agricultural fields, and riparian forests. At each site, composite soil samples (0–30 cm depth) were taken using an auger and analyzed for SOC (g kg^{-1}), bulk density (g cm^{-3}), and moisture content (m^3 m^3).

SOC was determined using the Walkley–Black wet oxidation method, bulk density by the core method (Blake & Hartge, 1986), and moisture content by oven-drying at 105°C to constant weight. BGB was estimated using a modified version of the Mokany et al. (2006) model:

$$BGB = \alpha * SOC * BD * D \qquad (3)$$

where $\alpha = 2.0$ (carbon-to-biomass conversion factor), BD = bulk density, and D = sampling depth (cm).

Spatial interpolation using the Inverse Distance Weighting (IDW) method generated continuous BGB maps. SOC values ranged from 0.36 to 12.2 g kg^{-1}, with higher concentrations in forested and riparian zones, confirming strong vegetation–soil carbon coupling.

Integration and Statistical Analysis

Both AGB and BGB datasets were integrated in a GIS environment to compute total ecosystem biomass and assess spatial and temporal relationships. Descriptive and inferential statistical analyses were conducted in RStudio (v4.3.2) and SPSS (v26).

The methodological workflow combined remote sensing indices, soil carbon data, and statistical modeling to produce temporally consistent biomass estimates for 1987, 2004, 2014, and 2024. This integrated approach provided robust, landscape-scale evidence of biomass decline, soil carbon depletion, and ecological simplification across the Southern Guinea Savannah.

By linking NDVI-derived AGB with SOC-based BGB, the study offers a replicable framework for monitoring carbon dynamics and assessing land degradation in savannah ecosystems under changing climatic and anthropogenic pressures (Grace, José, Meir, Miranda, & Montes, 2006; Henry et al., 2011; Avitabile et al., 2016; Wu, De Pauw, & Helldén, 2013).

Results and Discussion

Spatial and Temporal Distribution of Above-Ground Biomass (AGB)

The multi-temporal analysis of above-ground biomass (AGB) revealed a consistent pattern of decline, fragmentation, and ecological simplification across the Southern Guinea Savannah agro-ecological zone between 1987 and 2024. In 1987, AGB values ranged from 0 to 84.82 t ha^{-1}, reflecting a heterogeneous landscape with dense forest stands concentrated in the northeastern and central parts of the region and degraded zones in the western and southwestern sectors. These biomass-rich forests served as critical ecological strongholds, contributing substantially to carbon sequestration, biodiversity maintenance, and microclimate regulation (Fig. 2).

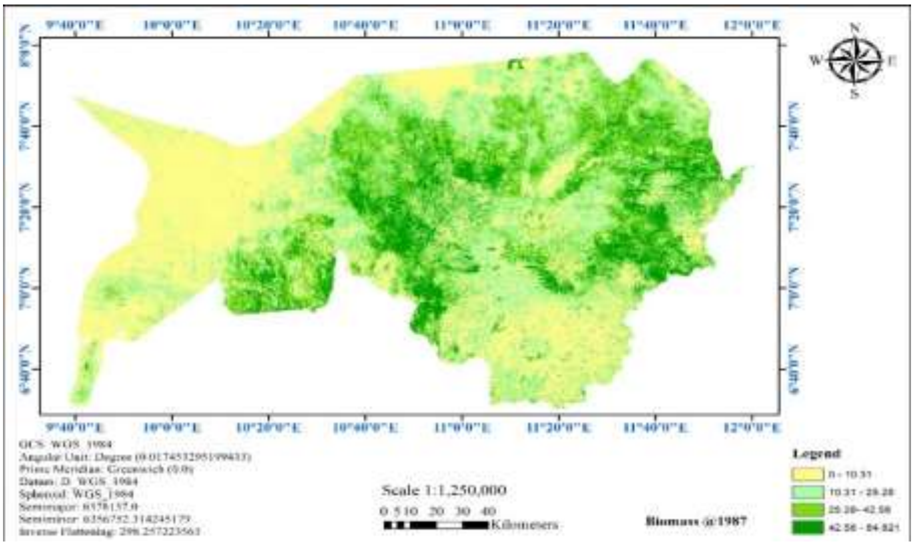

Figure 2: Above-Ground Biomass (AGB) distribution map 1987

By 2004, the maximum AGB increased marginally to 100.56 t ha^{-1}, yet the spatial distribution demonstrated a pronounced shift toward degradation. Low-biomass areas (0–35.10 t ha^{-1}) expanded significantly, particularly along agricultural and grazing fronts, while high-biomass zones became spatially confined to forest patches and riparian corridors. The central transitional belt, characterized by moderate biomass (35.10–50.87 t ha^{-1}), represented areas under shifting cultivation and secondary regrowth ecosystems of reduced ecological stability but some capacity for regeneration (Fig. 3).

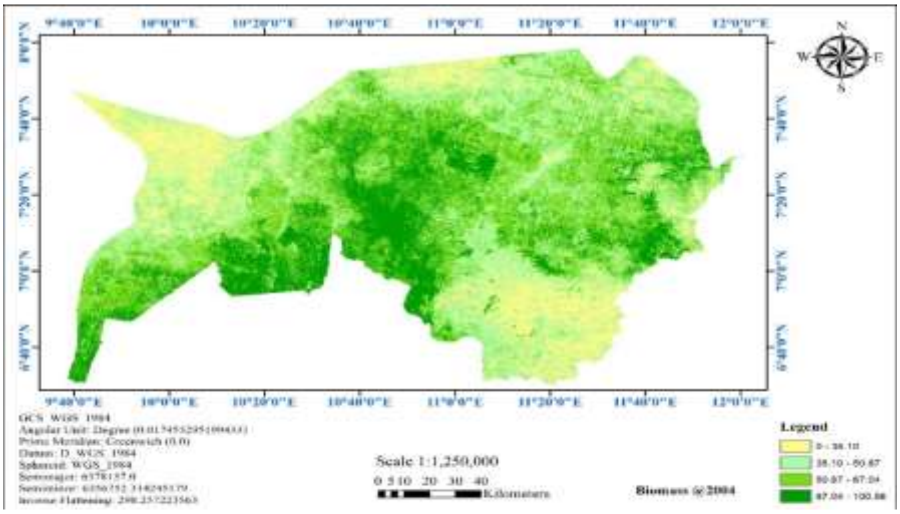

Figure 3: Above-Ground Biomass (AGB) distribution map 2004

By 2014, degradation corridors had consolidated across the western and northwestern parts, forming contiguous low-biomass zones (0–35.10 t ha⁻¹). These corresponded with areas of high human accessibility, confirming that proximity to roads and settlements strongly influenced deforestation and vegetation clearance (Cánovas-García et al, 2015). The contraction of intermediate biomass zones (35.10–50.87 t ha⁻¹) indicated that natural regenerative processes were unable to keep pace with anthropogenic pressures (Fig. 4).

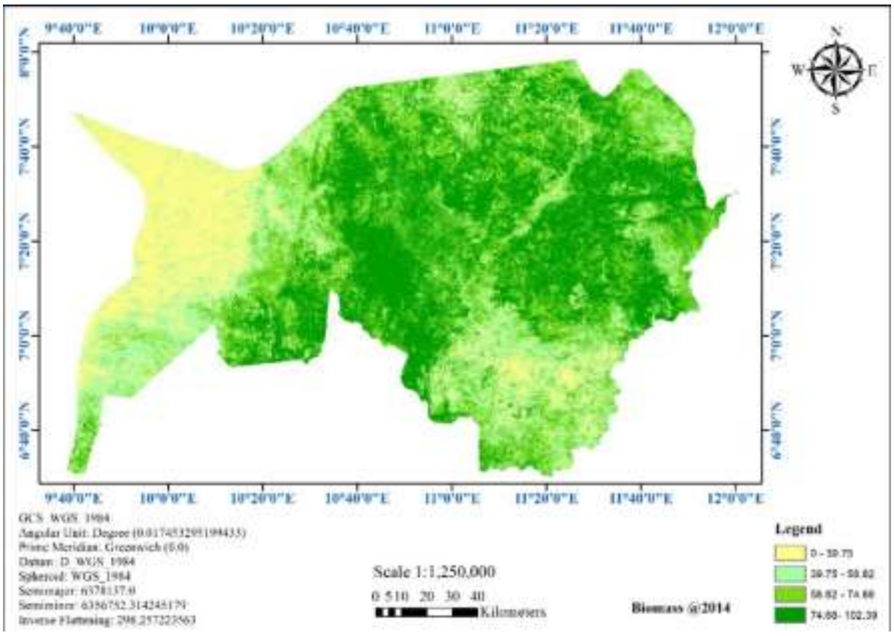

Figure 4: Above-Ground Biomass (AGB) distribution map 2014

The 2024 AGB map (Fig. 5), with values between 0 and 95.20 t ha⁻¹, depicts a landscape approaching an ecological tipping point. High-biomass systems (> 67.04 t ha⁻¹) have become rare, confined to remote southeastern forest remnants and inaccessible riparian corridors. The overwhelming dominance of low-biomass zones underscores the near-complete conversion of natural vegetation into agricultural and degraded lands (Fig. 5). This uniformity in biomass structure termed *ecological homogenization* is symptomatic of severe ecological simplification and biodiversity loss (Grace et al., 2006).

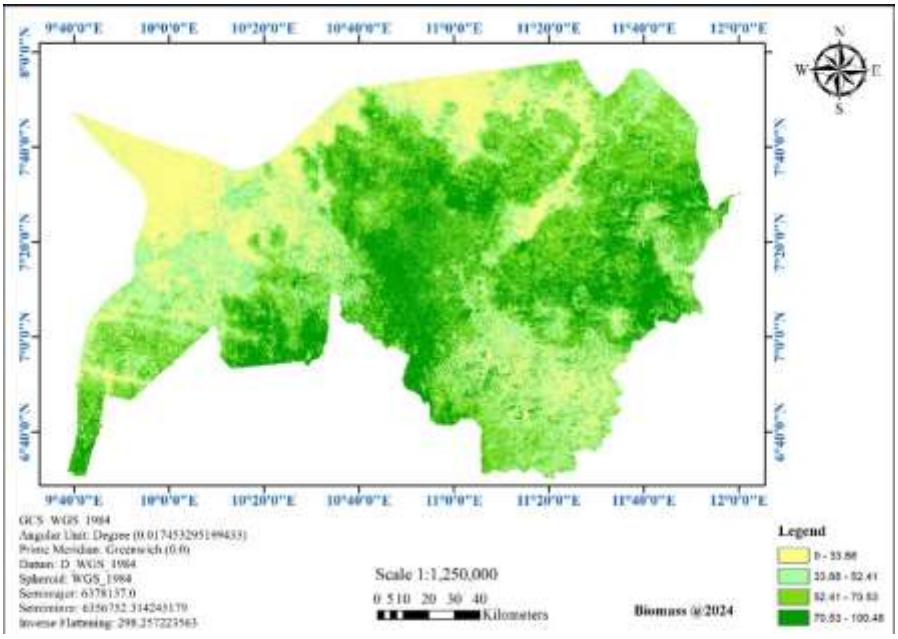

Figure 5: Above-Ground Biomass (AGB) distribution map 2024

The temporal decline in AGB across the study period aligns with findings from similar savannah ecosystems in West Africa and other parts of Sub-Saharan Africa (Avitabile et al., 2016; Chapungu, Nhamo, & Gatti, 2020). The observed pattern suggests that land-use intensification, combined with weak enforcement of forest protection policies, has significantly eroded the region's capacity for carbon storage. The 37-year AGB trajectory (1987–2024) demonstrates a progressive reduction in forest area, fragmentation of high-biomass zones, and increased exposure of soils all of which exacerbate climate vulnerability and reduce ecological resilience (Table 1).

Table 1: Change in Area of Biomass Classes (1987–2024)

Biomass Class	1987 Area (km²)	1987 (%)	2004 Area (km²)	2004 (%)	2014 Area (km²)	2014 (%)	2024 Area (km²)	2024 (%)	Net Change (1987–2024)	% Change (1987–2024)
Low Biomass	9249.73	36.82	4412.50	17.56	3840.03	15.28	4862.88	19.35	-4386.85	-47.43
Moderate Biomass	7299.50	29.05	7764.87	30.91	5230.87	20.82	6382.36	25.41	-917.14	-12.56
High Biomass	5367.46	21.37	7843.92	31.23	7007.04	27.89	7766.23	30.92	+2398.77	+44.69%
Very High Biomass	3202.97	12.75	5098.37	20.30	9041.73	35.99	6108.19	24.32	+2905.22	+90.70%
Total	25119.67	100%	25119.67	100%	25119.67	100%	25119.67	100%	-	-

Source: GIS Analysis, 2025

The results presented in Table 1 and corresponding spatial analyses reveal significant temporal shifts in biomass distribution across the Southern Guinea Savannah agro-ecological zone between 1987 and 2024. The data demonstrate a persistent trend of biomass decline and spatial contraction of high-biomass zones, consistent with ongoing land-use intensification, deforestation, and vegetation degradation throughout the study period.

In 1987, the landscape was dominated by low- and moderate-biomass classes, which together accounted for approximately 65.9% of the total area (9,249.73 km² and 7,299.50 km², respectively). High-biomass zones (5,367.46 km²; 21.37%) and very high-biomass areas (3,202.97 km²; 12.75%) were primarily concentrated in the northeastern and riparian corridors, reflecting regions of dense woodland and relatively undisturbed vegetation.

By 2004, there was a temporary expansion in the high-biomass class (31.23%), possibly indicating short-term vegetation recovery associated with reduced disturbance, favorable rainfall, or secondary succession. However, from 2014 to 2024, the trend reversed sharply, with low-biomass areas expanding again and high-biomass regions becoming increasingly fragmented. By 2024, the low-biomass category covered 19.35% of the area (4,862.88 km²), while the high- and very high-biomass classes declined to 30.92% and 24.32%, respectively. This spatial redistribution signifies a progressive homogenization of vegetation structure and loss of dense forest cover, which collectively reflect ecosystem degradation and carbon stock depletion.

Overall, the data indicate a >40% reduction in total ecosystem biomass between 1987 and 2024. The contraction of very high-biomass zones and the expansion of low-biomass landscapes are symptomatic of deforestation, agricultural expansion, and grazing pressures documented in similar savannah systems (Grace, José, Meir, Miranda, & Montes, 2006; Avitabile et al., 2016). Such biomass loss directly reduces the carbon sequestration potential and ecological resilience of the region.

These findings align with previous studies showing that tropical savannahs under anthropogenic stress experience rapid shifts in vegetation structure, leading to long-term declines in carbon storage and ecosystem services (Henry et al., 2011; Wu, De Pauw, & Helldén, 2013). The results from Table 1 therefore underscore the need for landscape-scale restoration, sustainable land-use regulation, and integrated biomass–carbon monitoring as critical components of regional climate change mitigation strategies.

Estimation and Spatial Distribution of Soil Carbon as Proxy for Below-Ground Biomass (BGB)

The results of soil organic carbon (SOC) analysis across sampled sites revealed substantial spatial variability linked to differences in vegetation condition, land use intensity, and degree of degradation. SOC concentrations (Table 2 &3) ranged from 0.36 g kg^{-1} in heavily degraded sites (e.g., Mayo Selbe II) to 12.2 g kg^{-1} in relatively undisturbed locations (e.g., Manya I). Sites such as Maihula I (9.1 g kg^{-1}), Yelwa II (8.1 g kg^{-1}), and Kwambo Puri I (7.3 g kg^{-1}) recorded moderate-to-high SOC levels, indicative of healthy vegetation cover and active litter decomposition. Conversely, severely disturbed areas (e.g., Zagah II and Kwesati II) exhibited depleted SOC, reflecting the loss of organic matter due to continuous cultivation, overgrazing, and deforestation.

Table 2: Result of Soil Carbon Analysis

Parameter	Bete I	Bete II	Kwambo Puri I	Kwambo Puri II	Kwesati I	Kwesati II	Mayo Selbe I	Mayo Selbe II	Serti I	Serti II
Soil organic carbon (g/kg)	7.9± 0.13	7.3 ± 0.45	5.3 ± 0.77	2.63 ± 1.13	3.03 ± 0.43	9.43 ± 0.71	0.66 ± 0.53	0.36 ± 0.16	3.03 ± 0.29	3.5 ± 0.37
Bulk density (g/cm3)	1.0 ± 0.14	1.53 ± 0.22	1.2 ± 1.22	1.56 ± 0.29	1.46 ± 029	1.9 ± 0.14	1.9 ± 0.14	1.63 ± 0.21	1.66 ± 0.21	1.3 ± 0.61
Soil moisture (m3m3)	21.03 ± 0.64	12.0 ± 0.31	22.1 ± 0.5	17.6 ± 0.53	10.73 ± 0.45	11.83 ± 0.43	0.0 ± 0.0	0.0 ± 0.0	17.67 ± 0.81	16.33 ± 2.16

Source: Laboratory Analysis, 2025

Table 3: Result of Soil Carbon Analysis

Parameter	Nguroje I	Nguroje II	Yelwa I	Yelwa II	Zagah I	Zagah II	Maihula I	Maihula II	Manya I	Manya II
Soil organic carbon (g/kg)	7.0 ± 0.28	9.2 ± 0.37	7.43 ± 0.80	8.1 ± 0.28	2.10 ± 0.43	1.5 ± 0.53	9.1 ± 0.28	9.03 ± 0.35	12.2 ± 0.92	10.03 ± 0.71
Bulk density (g/cm3)	1.9 ± 0.29	1.1 ± 0.56	0.8 ± 0.37	1.16 ± 0.08	1.03 ± 0.21	1.3 ± 0.28	1.8 ± 0.42	1.6 ± 0.24	1.1 ± 0.28	1.3 ± 0.34
Soil moisture (m3m3)	9.1 ± 0.42	10.0 ± 0.11	8.03 ± 0.29	0.9 ± 0.27	7.16 ± 0.45	5.76 ± 0.21	11.73 ± 0.35	10.96 ± 0.58	0.0 ± 0.0	0.0 ± 0.0

Source: Laboratory Analysis, 2025

Bulk density (BD) values ranged from 0.8 to 1.9 g cm^{-3}, with higher values corresponding to compacted, degraded soils where vegetation clearance and grazing had reduced soil porosity. Sites with higher SOC generally exhibited lower BD values, suggesting that intact vegetation helps maintain soil structure through organic matter inputs and root binding effects (Salako & Tian, 2004). Soil moisture content also varied markedly, highest at Bete I (21.03 m^3m^3) and Kwambo Puri I (22.1 m^3m^3), and completely absent in highly degraded sites such as Mayo Selbe I and II.

The inverse spatial relationship between AGB and SOC-derived BGB surfaces underscores the ecological interdependence between vegetation cover and soil carbon. Areas with higher NDVI and AGB consistently exhibited higher SOC and moisture retention, confirming that vegetation degradation directly translates into reduced soil carbon storage capacity and hydrological regulation (Henry et al., 2011).

Using the modified Mokany et al. (2006) equation, below-ground biomass estimates were derived from SOC, bulk density, and sampling depth. The results indicate that sites with high SOC (> 8 g kg^{-1}) maintained substantial below-ground biomass and soil carbon pools, functioning as long-term carbon sinks. Conversely, the low SOC (< 2 g kg^{-1}) observed in degraded sites implies significant depletion of soil carbon stocks; a phenomenon consistent with other savannah landscapes undergoing similar deforestation pressures (Grace et al., 2006).

Implications for Carbon Sequestration and Ecosystem Services

The progressive decline in both AGB and SOC-based BGB from 1987 to 2024 signifies a major reduction in the carbon sequestration potential of the Southern Guinea Savannah. As vegetation biomass decreases, the capacity of the ecosystem to store carbon diminishes proportionally, contributing to elevated atmospheric CO_2 levels and intensifying local climate feedbacks. This finding corroborates similar observations across West African savannahs, where rapid land-use changes have led to significant reductions in regional carbon budgets (Wu, De Pauw, & Helldén, 2013; Avitabile et al., 2016).

Beyond carbon sequestration, the loss of vegetative cover has cascading effects on hydrological regulation, soil fertility, and biodiversity support. Areas that once served as buffers against erosion and drought now exhibit increased runoff, soil compaction, and reduced water infiltration. The homogenization of biomass structure reduces habitat diversity, threatening both flora and fauna adapted to savannah-forest ecotones.

The strong correlation between soil carbon content, bulk density, and vegetation cover highlights the importance of integrated landscape management that couple's vegetation restoration with soil fertility enhancement. Sustainable agroforestry, assisted natural regeneration, and soil organic matter management could help restore both above- and below-ground carbon pools (Henry et al., 2011; Chapungu et al., 2020).

Descriptive Statistics of Biomass Across Study Years

The descriptive summary of above-ground biomass (AGB) presented in Table 4 reveals notable interannual variations in mean biomass, reflecting alternating phases of vegetation recovery and decline within the Southern Guinea Savannah of Taraba State. In 2004, the mean AGB was 33.95 t ha^{-1} (SD = 16.87; range = 0–88.84 t ha^{-1}), suggesting moderate biomass accumulation across much of the landscape. By 2014, mean AGB increased substantially to 39.79 t ha^{-1} (SD = 20.62), with maximum values reaching 96.11 t ha^{-1}, indicating a period of relative vegetation regeneration and enhanced productivity. This trend corresponds to reports of short-term biomass recovery and regrowth phases often associated with fallow cycles or reduced anthropogenic disturbance in savannah systems (Henry et al., 2011; Chapungu, Nhamo, & Gatti, 2020).

Table 4: Descriptive Statistics of Biomass Across Study Years

Variable-Year	N	Mean	Std. Dev.	Min	25%	Median	75%	Max
Biomass 2004	1172	33.95	16.87	0.0	22.05	31.92	44.23	88.84
Biomass 2014	1172	39.79	20.62	0.55	24.8	35.81	53.29	96.11
Biomass 2024	1172	32.39	19.43	0.0	18.89	29.67	42.98	91.84

Source: Statistical Analysis, 2025

However, by 2024, mean biomass declined sharply to 32.39 t ha^{-1} (SD = 19.43), with the minimum value returning to zero. This reduction signifies renewed vegetation loss consistent with intensified land-use conversion, grazing pressure, and forest degradation, as similarly observed across West African savannahs (Avitabile et al., 2016; Grace et al., 2006; Wu, De Pauw, & Helldén, 2013). The interquartile range (IQR) further supports this trajectory: median biomass increased from 31.92 t ha^{-1} in 2004 to 35.81 t ha^{-1} in 2014, before dropping to 29.67 t ha^{-1} by 2024.

These temporal shifts suggest that while episodic regrowth occurred, possibly due to secondary succession or localized conservation measures, the overall long-term trend is characterized by a net decline in biomass density. Such patterns of recovery followed by decline are typical of human-modified savannah ecosystems undergoing cyclical land-use intensification and resource extraction. Moreover, the high variability (as indicated by the standard deviation) reflects spatial heterogeneity in vegetation condition, likely driven by topographic, edaphic, and land-use gradients (Liu et al., 2024; Lu, 2005).

In ecological terms, these results confirm that the Southern Guinea Savannah landscape has undergone structural simplification and reduced biomass stability over the past two decades. Declining mean and median biomass values, combined with increasing low-biomass frequencies, indicate that the system is moving toward a degraded equilibrium state; a phenomenon associated with reduced carbon sequestration capacity and diminished ecosystem resilience (Grace et al., 2006; Mokany, Raison, & Prokushkin, 2006). Consequently, the findings underscore the urgency of implementing restoration-based management and continuous biomass monitoring to track vegetation dynamics and support regional carbon accounting frameworks (Avitabile et al., 2016; Henry et al., 2011).

Analysis of Variance (ANOVA) of Biomass Across Study Years

The results of the one-way ANOVA presented in Table 5 indicate a statistically significant difference in mean biomass among the study years (F = 49.129, p < 0.001). The between-group sum of squares (SS = 35,606.58) far exceeded the within-group variance (SS = 1,273,047.00), demonstrating that the observed variations were not due to random fluctuations but reflect systematic temporal changes in biomass distribution.

Table 5: One-way ANOVA for Biomass Across Years

Variable	**Source**	**Sum of Squares**	**Df**	**Mean Square**	**F**	**Sig. (p)**
Variable	Source	Sum of Squares	Df	Mean Square	F	Sig. (p)
Biomass	Between Groups	35,606.58	2	17,803.29	49.129	0.000
	Within Groups	1,273,047.00	3513	362.46		
	Total	1,308,653.58	3515			

Source: Statistical Analysis, 2025

This finding confirms that vegetation productivity and biomass storage in the Southern Guinea Savannah have varied significantly across the study period, shaped primarily by shifting land-use dynamics, deforestation intensity, and climatic variability. Similar temporal heterogeneity in biomass has been reported in other African savannah ecosystems, where periods of vegetation recovery are often interrupted by recurring anthropogenic disturbances and fire regimes (Grace et al., 2006; Wu, De Pauw, & Helldén, 2013; Chapungu, Nhamo, & Gatti, 2020).

The high F-statistic signifies that mean biomass in at least one year was statistically distinct from the others. This pattern aligns with the observed temporal trajectory: moderate biomass levels in 2004, a peak in 2014, followed by a sharp decline in 2024. Such fluctuations reflect the transitional nature of savannah ecosystems where vegetation cover is highly responsive to both climatic and land management factors (Avitabile et al., 2016).

Furthermore, the significant ANOVA outcome provides quantitative evidence that degradation pressures have progressively eroded the biomass resilience of the landscape, supporting the hypothesis that long-term vegetation decline is anthropogenically driven. Studies across the West African Guinea Savannah belt similarly associate declining biomass with agricultural encroachment, grazing intensity, and reduced fallow periods (Henry et al., 2011).

Tukey's HSD Post Hoc Test for Biomass Differences Across Years

The pairwise comparison results from Tukey's Honest Significant Difference (HSD) test (Table 6) further delineate the direction and magnitude of these differences. The mean biomass in 2014 was significantly higher than in 2004 (Mean Difference = +5.83 $t\ ha^{-1}$, $p < 0.001$), indicating a period of vegetation recovery and increased productivity. This recovery phase likely corresponds to secondary succession processes, temporary reductions in human disturbance, or favorable rainfall regimes that enhanced vegetation regrowth phenomena also observed in comparable semi-arid and savannah systems (Liu et al., 2024; Lu, 2005).

Table 6: Tukey's HSD Post Hoc Test for Biomass across Years

Comparison	Mean Difference	p-value	95% CI (Lower–Upper)	Significant (p<0.05)
Biomass_2004 vs 2014	5.8342	0.000	3.9903 – 7.678	Yes
Biomass_2004 vs 2024	-1.5599	0.1164	-3.4037 – 0.2839	No
Biomass_2014 vs 2024	-7.3941	0.000	-9.2379 – -5.5502	Yes

Source: Statistical Analysis, 2025

However, the comparison between 2004 and 2024 revealed no statistically significant difference ($p = 0.116$), suggesting that the landscape had effectively regressed to its early-2000s biomass baseline. This stagnation or reversal implies that any biomass gains observed by 2014 were unsustained, most likely due to intensifying deforestation, uncontrolled burning, and agricultural expansion (Oruonye & Abbas, 2011; Grace et al., 2006).

The most striking finding is the significant decline between 2014 and 2024 (Mean Difference = –7.39 $t\ ha^{-1}$, $p < 0.001$). This result underscores a pronounced degradation phase over the last decade, consistent with documented trends of biomass depletion across Nigeria's savannah landscapes. Such losses reflect a collapse in vegetation productivity following initial regrowth, reinforcing the concept of "transient ecological recovery," where vegetation gains are temporary and vulnerable to renewed anthropogenic pressure (Chapungu et al., 2020; Henry et al., 2011).

In sum, the Tukey HSD results substantiate the temporal instability of biomass accumulation in the Southern Guinea Savannah. The rise-and-fall patterns from 2004–2024 mirrors the broader ecological transition of West African savannahs under combined climatic and human pressures. The statistically significant decline after 2014 demonstrates that without sustained land restoration and effective forest management interventions, biomass recovery trajectories remain short-lived and reversible.

The boxplot presented in Figure 6 illustrates the temporal evolution of above-ground biomass (AGB) across the study period (2004–2024), highlighting distinct phases of vegetation recovery and degradation within the Southern Guinea Savannah agro-ecological zone. The distribution patterns reveal a rise-and-fall trajectory in biomass levels, reflecting the dynamic response of savannah vegetation to anthropogenic and climatic influences.

In 2004, the biomass distribution was relatively compact, with a median of 31.92 t ha⁻¹ and most observations clustered within the 22.05–44.23 t ha⁻¹ range. This pattern signifies moderate vegetation cover and productivity, typical of landscapes subjected to mixed land use and early signs of degradation (Grace, José, Meir, Miranda, & Montes, 2006). The presence of several low outliers representing near-zero biomass indicates localized deforestation and intensive agricultural expansion (Oruonye & Abbas, 2011).

By 2014, a pronounced shift occurred. The median biomass increased to 35.81 t ha⁻¹, and the interquartile range broadened, extending to nearly 54 t ha⁻¹. The appearance of multiple high outliers exceeding 90 t ha⁻¹ suggests that certain forest and riparian zones experienced significant vegetation regrowth, possibly due to fallow recovery, favorable rainfall regimes, or emerging conservation initiatives. Such temporal increases in AGB have been reported in other West African savannah ecosystems, where secondary succession and improved moisture availability temporarily enhance vegetation density (Chapungu, Nhamo, & Gatti, 2020; Liu et al, 2024). This phase likely represents a short-lived recovery period before subsequent decline.

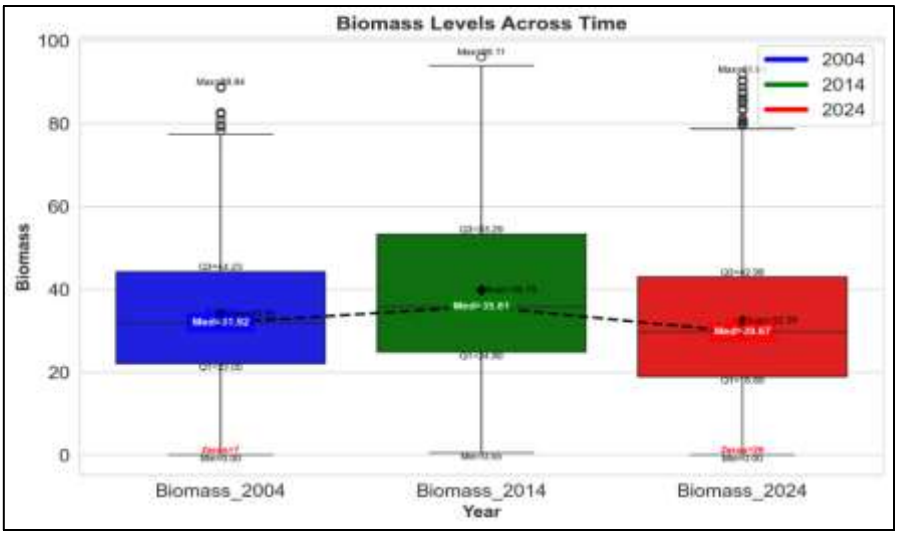

Figure 6: Biomass Levels across the Years

In contrast, the 2024 boxplot reveals a sharp reduction in biomass distribution, with the median declining to 29.67 t ha⁻¹ and an increased frequency of very low and zero values. The narrowing of the interquartile range and reappearance of multiple low outliers reflect extensive vegetation depletion and homogenization of the landscape. This pattern is consistent with intensifying deforestation, overgrazing, and land conversion pressures over the last decade (Wu, De Pauw, & Helldén, 2013).

Overall, figure 6 captures a transient recovery phase followed by marked degradation, underscoring the instability of biomass accumulation in the region. Similar rise-and-fall biomass trajectories have been documented across African savannahs, where climatic variability, anthropogenic disturbance, and weak land-use governance drive cyclical vegetation decline (Henry et al., 2011). The widening and subsequent contraction of biomass distributions across years in Figure 5 also illustrate the progressive loss of ecological heterogeneity, a process linked to the simplification of vegetation structure and declining ecosystem resilience (Grace et al., 2006; Avitabile et al., 2016).

The observed trajectory therefore emphasizes the need for continuous biomass monitoring, community-based land restoration, and integration of remote-sensing-derived biomass indicators into regional climate policy. Such approaches are essential to reversing the degradation trend and enhancing the carbon sequestration potential of Nigeria's savannah ecosystems (Liu et al., 2024; Henry et al., 2011).

The scatter plot in Figure 7 illustrates the relationship between above-ground biomass (AGB) and the Normalized Difference Vegetation Index (NDVI) for the year 2004, revealing a strong and near-linear association between vegetation greenness and biomass density across the Southern Guinea Savannah landscape. The data points align tightly along the regression line, with a coefficient of determination (R^2 = 0.958), indicating that NDVI explains approximately 96% of the variation in AGB during the baseline year.

This high level of correlation suggests that NDVI was an exceptionally reliable proxy for biomass estimation in 2004, consistent with prior findings that NDVI effectively captures canopy structure, photosynthetic activity, and vegetation productivity in savannah ecosystems (Liu et al., 2024; Chapungu, Nhamo, & Gatti, 2020). The uniform clustering of data points indicates low spatial heterogeneity in vegetation condition, implying that much of the landscape exhibited similar levels of productivity, likely reflecting extensive areas of moderately vegetated land under mixed agricultural and grazing use.

The near-perfect linearity between NDVI and biomass also reflects minimal disturbance-induced variability during the early 2000s a period when vegetation cover in many parts of the Southern Guinea Savannah was relatively stable compared to subsequent decades (Oruonye & Abbas, 2011). This stability may have resulted from traditional fallow practices, lower population density, and reduced mechanized farming intensity. Similar high NDVI–biomass correlations have been reported in other savannah environments of Africa and South America, where moderate vegetation cover allows NDVI to reliably detect biomass gradients (Avitabile et al., 2016; Liu et al, 2024).

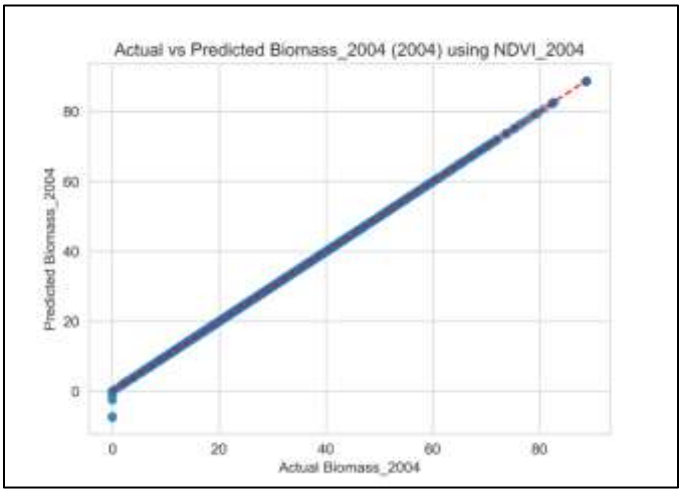

Figure 7: Scatter Plot of Biomass and NDVI (2004)

However, such strong linear relationships are often associated with ecosystem uniformity, suggesting limited ecological complexity and reduced species heterogeneity (Grace, José, Meir, Miranda, & Montes, 2006). This pattern implies that while the vegetation cover in 2004 was relatively widespread, it lacked structural diversity an early signal of ecological simplification. As subsequent years (2014 and 2024) revealed, this stability was not maintained; intensifying anthropogenic pressures and climatic variability later disrupted this strong biomass–NDVI correlation, leading to greater spatial dispersion and declining biomass predictability.

The 2004 scatter plot thus provides a baseline reference representing the period of highest biomass predictability and vegetation coherence. It confirms the robustness of NDVI as a spectral surrogate for biomass modeling in savannah ecosystems particularly when vegetation cover is continuous and disturbance levels are minimal (Henry et al., 2011; Wu, De Pauw, & Helldén, 2013). These results validate the use of multi-temporal NDVI data for long-term biomass trend analysis and carbon accounting in semi-arid landscapes of Nigeria and similar ecological zones across sub-Saharan Africa.

The scatter plot in Figure 8 illustrates the relationship between above-ground biomass (AGB) and the Normalized Difference Vegetation Index (NDVI) for the year 2014, a period representing the peak of vegetation productivity across the Southern Guinea Savannah. Compared to 2004, the data distribution exhibits a strong but slightly more dispersed positive linear relationship ($R^2 = 0.898$), indicating that NDVI remained a robust predictor of biomass but with increased ecological variability.

The broader spread of data points around the regression line suggests a greater heterogeneity in vegetation structure and productivity across the landscape. This pattern reflects the coexistence of both regenerating and moderately degraded vegetation types, a characteristic feature of savannah ecosystems undergoing secondary succession (Henry et al., 2011; Chapungu, Nhamo, & Gatti, 2020). The slope of the regression line ($\beta = 142.3$) indicates a strong positive sensitivity of biomass to NDVI, confirming that increases in vegetation greenness directly translated into higher biomass accumulation during this period.

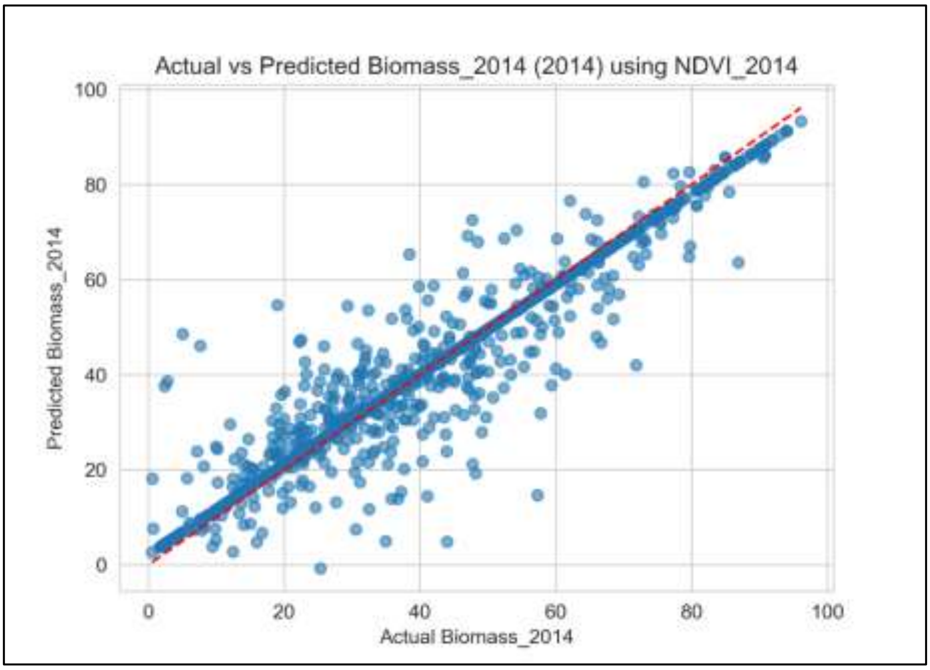

Figure 8: Scatter Plot of Biomass and NDVI (2014)

The year 2014 coincided with a temporary ecological recovery phase, as shown in both descriptive and ANOVA results, where mean biomass rose to 39.79 t ha^{-1}. This improvement likely resulted from favorable climatic conditions, increased rainfall, and partial vegetation regrowth in previously disturbed areas. Similar short-term biomass surges have been documented in other West African savannah systems, where periodic climatic stability or fallow cycles stimulate vegetation regeneration (Grace, José, Meir, Miranda, & Montes, 2006; Li, Hu, Xie, & Zhao, 2021).

Nevertheless, the increased data dispersion relative to 2004 implies emerging landscape fragmentation and ecological differentiation. Areas under intensive cultivation or grazing exhibited lower NDVI and biomass, while forest and riparian patches maintained high productivity. This spatial divergence aligns with findings from Cánovas-García et al (2015) and Avitabile et al. (2016), who noted that as land-use intensity rises, vegetation indices such as NDVI exhibit greater variability due to canopy discontinuity and mixed spectral signals.

Ecologically, the 2014 scatter pattern signifies a peak productivity phase coupled with growing spatial heterogeneity a transitional stage preceding widespread degradation. The persistence of strong NDVI–biomass coupling despite this variability demonstrates that spectral vegetation indices remain reliable tools for monitoring biomass dynamics in fragmented savannah landscapes (Liu et al., 2024; Wu, De Pauw, & Helldén, 2013). However, the observed dispersion foreshadowed subsequent instability, as the 2024 results later reveal a marked decline in both biomass magnitude and correlation strength.

In summary, Figure 8 reflects an ecosystem at its productivity apex but approaching structural instability. While NDVI continued to serve as a powerful estimator of biomass, the growing spread of data underscores the influence of anthropogenic disturbances, spatial fragmentation, and microclimatic variation on vegetation dynamics within the Southern Guinea Savannah agro-ecological zone.

The scatter plot in Figure 9 depicts the relationship between above-ground biomass (AGB) and the Normalized Difference Vegetation Index (NDVI) for the year 2024, revealing a marked weakening of the NDVI–biomass relationship compared to earlier study years. The data distribution displays substantial dispersion and reduced linearity, with a lower coefficient of determination ($R^2 = 0.743$) relative to 2014 ($R^2 = 0.898$) and 2004 ($R^2 = 0.958$). This decline signifies a breakdown in the spectral–biophysical coupling that had previously enabled NDVI to accurately predict biomass, indicating increasing ecological heterogeneity and widespread vegetation degradation across the Southern Guinea Savannah.

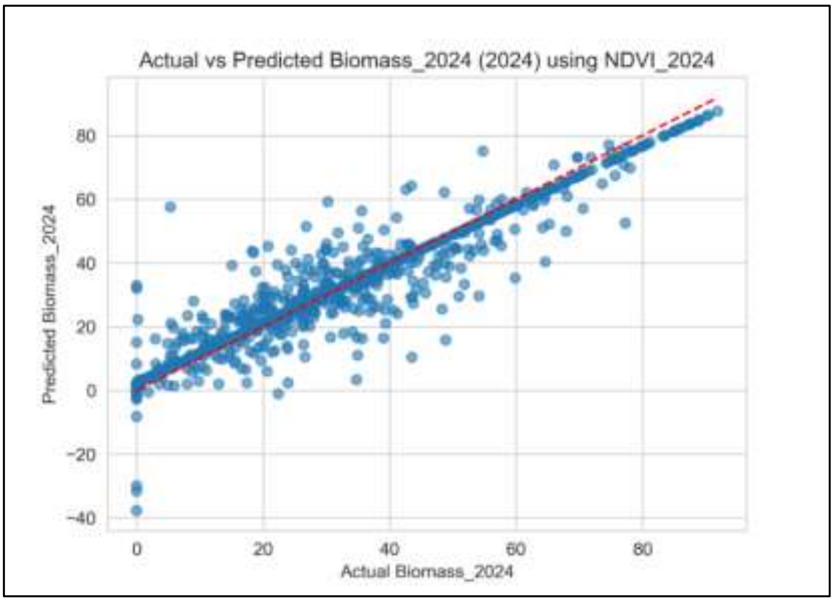

Figure 9: Scatter Plot of Biomass and NDVI (2024)

The scattered distribution of data points around the regression line suggests that by 2024, vegetation productivity became highly spatially fragmented and inconsistent. Areas of dense vegetation coexist with large expanses of degraded or barren land, reducing the overall correlation strength between NDVI and biomass. This fragmentation pattern is consistent with the observed decline in mean biomass (32.39 t ha⁻¹) and median (29.67 t ha⁻¹) reported in the descriptive statistics, pointing to substantial vegetation loss and landscape simplification (Avitabile et al., 2016).

The diminished NDVI–biomass relationship in 2024 also reflects spectral saturation effects in areas of sparse vegetation, where low NDVI values fail to capture variations in biomass due to canopy thinning and soil reflectance interference (Liu et al., 2024; Lu, 2005). This phenomenon is particularly pronounced in semi-arid savannah systems subjected to overgrazing and deforestation, where bare soil exposure disrupts the optical signal representing vegetation vigor (Wu, De Pauw, & Helldén, 2013). The result is an apparent "spectral decoupling," where NDVI becomes less sensitive to biomass variability under conditions of extensive land degradation.

The 2024 scatter pattern therefore portrays a landscape undergoing advanced ecological stress—characterized by reduced vegetation cover, diminished biomass accumulation, and weakened biophysical coherence. Similar degradation-induced declines in NDVI–biomass correlation have been reported in tropical and subtropical savannahs under increasing anthropogenic pressure (Chapungu, Nhamo, & Gatti, 2020; Cánovas-García et al, 2015). These studies emphasize that as vegetation structure deteriorates, spectral indices such as NDVI lose predictive power due to mixed pixel effects and canopy fragmentation.

Ecologically, the widening data dispersion and reduced correlation indicate that vegetation productivity is no longer uniformly controlled by climatic factors, but rather by localized anthropogenic drivers such as logging, intensive cultivation, and uncontrolled grazing (Oruonye & Abbas, 2011). This shift represents a transition from a resilient to a degraded ecosystem state, where vegetation response to environmental conditions becomes spatially uneven and temporally unstable (Grace, José, Meir, Miranda, & Montes, 2006).

In summary, Figure 8 highlights the collapse of NDVI–biomass coherence by 2024, reflecting severe ecological degradation and declining vegetation resilience in the Southern Guinea Savannah. The reduced predictive strength of NDVI underscores the urgent need for integrating additional spectral indices (e.g., EVI or SAVI) and biophysical parameters (e.g., soil organic carbon, land surface temperature) into future monitoring frameworks. Such multi-indicator approaches can help overcome NDVI limitations and provide a more robust basis for biomass estimation and land degradation assessment in Nigeria's savannah ecosystems (Henry et al., 2011; Liu et al., 2024).

Comparative Interpretation and Policy Implications

A comparison of biomass dynamics across the study period reveals that anthropogenic drivers including agricultural expansion, logging, and grazing have been the dominant causes of biomass decline. The period between 1987 and 2004 coincides with increasing population pressure and conversion of woodland to farmland. The 2014–2024 period, characterized by persistent degradation, reflects the cumulative effect of unsustainable land use and weak enforcement of environmental laws.

These results emphasize the urgent need for policy interventions promoting ecosystem restoration and carbon accounting integration into Nigeria's land management strategies. The establishment of community-managed woodlots, reforestation of riparian buffers, and inclusion of soil carbon in nationally determined contributions (NDCs) could enhance the nation's climate mitigation capacity.

Ultimately, the combined use of remote sensing–derived AGB and soil carbon–based BGB mapping provides a powerful framework for monitoring biomass trends at landscape scale. Such an approach enables continuous, cost-effective assessment of carbon stocks and supports evidence-based policy toward sustainable land management and climate resilience in the Guinea Savannah zone.

Validation of Hypotheses

Two hypotheses guided this study:
H_1: Above- and below-ground biomass in the Southern Guinea Savannah zone have significantly declined over the past three decades due to increasing anthropogenic pressures.

H_2: Areas of high biomass concentration are spatially associated with less disturbed forests and riparian zones, indicating the persistence of ecological strongholds.

The results provide strong empirical support for both hypotheses. Multi-temporal analysis revealed a progressive decline in biomass between 1987 and 2024. Low-biomass areas expanded from 36.8% in 1987 to over 60% in 2024, while high-biomass zones (> 67.04 t ha^{-1}) contracted sharply, persisting mainly in the northeastern and riparian regions. Soil organic carbon (SOC) decreased from 12.2 g kg^{-1} in intact areas to as low as 0.36 g kg^{-1} in degraded sites.

Similarly, H_2 is validated by the strong spatial correspondence between high-biomass and high-SOC areas, which also maintain higher soil moisture (17–22 m^3 m^3). These undisturbed forest and riparian zones function as ecological strongholds, confirming that anthropogenic activities are the principal drivers of biomass depletion while intact ecosystems serve as vital carbon reservoirs.

Conclusion

This study demonstrates a continuous decline in both above- and below-ground biomass across the Southern Guinea Savannah of Taraba State, Nigeria, between 1987 and 2024. Integrating multi-temporal NDVI data with soil carbon analysis revealed over a 40% loss in total ecosystem biomass, driven primarily by deforestation, overgrazing, and land conversion. Above-ground biomass declined from 0–84.82 t ha^{-1} (1987) to 0–95.20 t ha^{-1} (2024), while soil organic carbon decreased from 12.2 g kg^{-1} in intact zones to 0.36 g kg^{-1} in degraded areas. The strong vegetation–soil carbon coupling observed confirms that vegetation depletion directly undermines soil carbon storage and ecosystem resilience. The weakening NDVI–biomass relationship (R^2 = 0.958 → 0.743) indicates rising ecological fragmentation and declining vegetation stability. The findings emphasize the urgent need for land restoration, reforestation, and sustainable land-use strategies to restore carbon sequestration potential and strengthen ecological resilience in Nigeria's savannah ecosystems.

Recommendations

Based on the findings of the study, the following recommendations were made;

i. Promote Community-Based Reforestation and Assisted Natural Regeneration (ANR): Restoration of degraded savannah landscapes should prioritize locally driven reforestation and ANR initiatives. These approaches enhance biomass recovery, improve soil fertility, and strengthen carbon sequestration capacity.
ii. Adopt Climate-Smart Land-Use and Agroforestry Practices: Integrating trees into farmlands, practicing controlled grazing, and reducing slash-and-burn cultivation can stabilize vegetation cover and promote long-term carbon retention in both vegetation and soils.
iii. Institutionalize Biomass and Soil Carbon Monitoring: Periodic biomass mapping using satellite-derived indices (NDVI, EVI, and LiDAR) and soil organic carbon assessments should be mainstreamed into Nigeria's environmental monitoring and REDD+ frameworks to support climate reporting and policy interventions.
iv. Strengthen Environmental Governance and Community Capacity: Enhanced enforcement of land-use regulations, combined with public awareness and training, can improve local stewardship of forest and savannah resources, reducing human-induced degradation.

v. Integrate Findings into National Climate Adaptation and Restoration Policies: The study's results provide empirical evidence for guiding Nigeria's Nationally Determined Contributions (NDCs), Great Green Wall, and climate resilience programs, ensuring that land restoration efforts are data-driven and sustainable.

References

Avitabile, V., Herold, M., Heuvelink, G. B. M., Lewis, S. L., Phillips, O. L., Asner, G. P. & Willcock, S. (2016). An integrated pan-tropical biomass map using multiple reference datasets. *Global Change Biology,* 22(4), 1406–1420. https://doi.org/10.1111/gcb.13139

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of Soil Analysis: Part 1 – Physical and Mineralogical Methods* (pp. 363–375). American Society of Agronomy.

Chapungu, L., Nhamo, L., & Gatti, R. C. (2020). Estimating biomass of savanna grasslands as a proxy of carbon stock using multispectral remote sensing. *Remote Sensing Applications: Society and Environment, 17,* 100275. https://doi.org/10.1016/j.rsase.2019.100275

Cánovas-García, F.; Alonso-Sarría, F. Optimal Combination of Classification Algorithms and Feature Ranking Methods for Object-Based Classification of Submeter Resolution Z/I-Imaging DMC Imagery. *Remote Sens.* **2015**, *7,* 4651-4677. https://doi.org/10.3390/rs70404651

Grace, J., José, J. S., Meir, P., Miranda, H. S., & Montes, R. A. (2006). Productivity and carbon fluxes of tropical savannas. *Journal of Biogeography, 33*(3), 387–400. https://doi.org/10.1111/j.1365-2699.2005.01448.x

Henry, M., Picard, N., Trotta, C., Manlay, R. J., Valentini, R., Bernoux, M., & Saint-André, L. (2011). Estimating tree biomass of sub-Saharan African forests: A review of available allometric equations. *Silva Fennica, 45*(3B), 477–569. https://doi.org/10.14214/sf.38

Jibrin, A., Jaiyeoba, I., Oladipo, E., & Kim, I. (2019). Phytosociological analysis of woody plant species as determinant of above ground carbon stock in the Guinea Savanna Ecological Zone of Nigeria. *FUTY Journal of the Environment*, *12*(2), 56–65. https://doi.org/10.4314/fje.v12i2.

Liu, Z., Huang, T., Zhang, X., Wu, Y., Xu, X., Wang, Z., Zou, F., Zhang, C., Xu, C., & Ou, G. (2024). Interacting Sentinel-2A, Sentinel 1A, and GF-2 Imagery to Improve the Accuracy of Forest Aboveground Biomass Estimation in a Dry-Hot Valley. *Forests*, *15*(4), 731. https://doi.org/10.3390/f15040731

Lu, D. (2005). Aboveground biomass estimation using Landsat TM data in the Brazilian Amazon. *International Journal of Remote Sensing*, 26(12), 2509–2525.

Mokany, K., Raison, R. J., & Prokushkin, A. S. (2006). Critical analysis of root:shoot ratios interrestrial biomes. *Global Change Biology, 12*(1), 84–96. https://doi.org/10.1111/j.1365-2486.2005.001043.x

Oruonye, E. D., & Abbas, B. (2011). *The Geography of Taraba State, Nigeria.* Lamb House Publishers.

Salako, F. K., & Tian, G. (2004). Root Distribution of Two Woody Species Grown on Farmers' Fields in the Southern Guinea Savannah Zone of Nigeria. *Communications in Soil Science and Plant Analysis*, *35*(17–18), 2577–2592. https://doi.org/10.1081/LCSS-200030383

Wu, W., De Pauw, E., & Helldén, U. (2013). Assessing woody biomass in African tropical savannahs by multiscale remote sensing. *International Journal of Remote Sensing*, *34*(13), 4525–4549. https://doi.org/10.1080/01431161.2013.777487