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Spatial Assessment of Carbon Sequestration Dynamics in Southern Guinea Savannah Agro-Ecological Zone of Taraba State, Nigeria

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Abstract

This study assessed the spatial and temporal dynamics of carbon sequestration in the Southern Guinea Savannah agro-ecological zone of Taraba State, Nigeria, between 1987 and 2024. Multi-date Landsat imagery was classified into land use and land cover categories, and aboveground biomass was estimated and converted to carbon using the Intergovernmental Panel on Climate Change (IPCC) default factor of 0.5. The results revealed significant fluctuations in carbon storage across the study period. Carbon stocks increased between 2004 and 2014, reflecting localized vegetation recovery and temporary gains in biomass. However, this growth was unsustained, as carbon sequestration declined sharply between 2014 and 2024, reverting to levels comparable with 2004. The trajectory highlights the strong influence of deforestation, agricultural expansion, and land degradation, compounded by climatic variability. Statistical analysis confirmed significant differences in carbon sequestration across years, with the most substantial decline occurring between 2014 and 2024. The findings underscore the vulnerability of the Guinea Savannah's carbon sink capacity and its susceptibility to unsustainable land use practices. The study recommends sustainable forest management, afforestation and reforestation, community-based conservation, and climate-smart agriculture to safeguard carbon stocks. These measures are critical for enhancing ecosystem resilience and contributing to Nigeria's climate mitigation and adaptation goals.

Keywords: *Biomass dynamics, Climate change mitigation, Carbon sequestration, Land use and land cover change & Southern Guinea Savannah*

Introduction

Climate change, driven primarily by increasing atmospheric concentrations of greenhouse gases such as carbon dioxide, remains one of the most pressing environmental challenges of the twenty-first century [1]. Terrestrial ecosystems play a crucial role in mitigating climate change by sequestering carbon in both biomass and soil organic matter. Savannah ecosystems, in particular, are dynamic landscapes that act as either carbon sinks or sources depending upon land use, climatic variability, and management practices. Nigeria's Guinea Savannah, which forms a broad transitional belt between the humid forest in the south and the drier Sudan and Sahel savannahs in the north, is a significant ecological zone where pressures of agriculture, grazing, and settlement intersect with climate dynamics to influence carbon sequestration potential [2]. The Southern Guinea Savannah (SGS) agro-ecological zone is characterized by relatively high rainfall lasting six to eight months, tall grasses interspersed with trees, and soils that, although fertile, are vulnerable to degradation if unsustainably managed [3]. Taraba State lies across multiple ecological zones, including the Southern and Northern Guinea Savannahs and the Montane Forest, giving it diverse topography, rainfall distribution, and vegetation patterns that influence carbon sequestration dynamics.

Recent climate analyses in Taraba State reveal significant changes in precipitation and temperature that directly affect the carbon balance of the landscape. Asa and Zemba [4] found that annual rainfall ranged from 733 mm to 2238 mm across different stations in southern Taraba, with rainy days spanning between 164 and 262 days. Importantly, the onset of rainfall has shifted later in the past decade, while mean temperatures exhibit a consistent upward trend across all stations, suggesting increasing evapotranspiration and moisture stress [4]. Complementary findings by the Global Journal of Science Frontier Research indicate rising temperatures across most stations in Taraba, except for Gembu in the highlands, and evidence of delayed rainfall onset in many areas, with a general shortening of the rainy season length. These climatic changes reduce vegetation productivity, alter biomass growth, and accelerate soil organic carbon decomposition, thereby weakening the ecosystem's ability to function as a net carbon sink.

In parallel, remote sensing and land use/land cover studies have highlighted rapid forest degradation and vegetation loss in Taraba State. Ojeh et al [5] documented significant declines in forest cover in the Kurmi Local Government Area between 1999 and 2019, with corresponding increases in bare land and built-up areas. Abba et al [6] reported that thick forest cover in the central part of Taraba declined dramatically from over 80% in 2006 to much lower levels by 2018, largely replaced by fragmented vegetation and bare surfaces. Similarly, Musa, Saddiq, and Abubakar [7] found marked vegetation loss in Gashaka Gumti National Park, even within protected zones, due to encroachment and anthropogenic pressures.

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Such land cover transitions reduce aboveground biomass carbon stocks, diminish litter input into soils, and exacerbate soil organic carbon depletion.

At the same time, empirical studies in Taraba and other parts of Nigeria have revealed both the potential and vulnerability of carbon sequestration in savannah ecosystems. Yani, Yekini, and Dishan [8] assessed aboveground, belowground, and soil carbon stocks across three ecological zones in Taraba and found that Montane Forest reserves had significantly higher sequestration potential than Guinea Savannah zones, underscoring the ecological gradient in carbon storage. Lawal [9] showed that conservation tillage and cover crops in the Northern Guinea Savannah improved soil organic carbon pools, pointing to management as a key determinant of sequestration capacity. Danjuma [3] further demonstrated that land use type and soil depth significantly influence carbon stocks in Katsina's Guinea Savannah, with croplands and degraded lands storing far less carbon than forest or fallow land.

Despite these insights, major knowledge gaps remain. Most existing studies provide static carbon stock estimates without examining the temporal dynamics of sequestration across decades of land use change and climatic variation. In addition, spatial heterogeneity in carbon sequestration across soils, vegetation types, and land use mosaics of Taraba's Southern Guinea Savannah remains poorly mapped. Furthermore, while several localized soil fertility and land degradation studies have been undertaken in Taraba [10], few have systematically integrated climate trend data with land cover change and carbon sequestration potential. This creates a serious research gap, as the Southern Guinea Savannah in Taraba is undergoing rapid transformation through deforestation, agricultural expansion, and unsustainable exploitation, yet its carbon sequestration potential and changing role in climate regulation remain underexplored.

Therefore, this study undertakes a spatially explicit assessment of carbon sequestration dynamics in the Southern Guinea Savannah agro-ecological zone of Taraba State. By integrating spatial analysis of land cover change with carbon stock estimation and climatic trends, the research provides crucial evidence of how one of Nigeria's most important ecological zones is shifting from a carbon sink towards a potential carbon source. This linkage highlights the urgency of sustainable land management, forest conservation, and policy interventions that can mitigate further carbon losses while enhancing the adaptive capacity of local ecosystems and communities. In doing so, the study directly addresses a pressing research problem: the lack of spatially and temporally grounded data on carbon sequestration dynamics in Taraba's Southern Guinea Savannah, which is vital for both national climate commitments and global mitigation strategies.

Description of the Study Area

The study was conducted in the Southern Guinea Savannah agro-ecological zone of Taraba State, Nigeria. This zone occupies the southern part of the state and encompasses the Local Government Areas (LGAs) of Wukari, Donga, Takum, Kurmi, Bali, Gashaka, and Sardauna. Geographically, it lies between latitudes 6°30′N and 8°30′N and longitudes 10°00′E and 11°30′E, covering an estimated area of approximately 25,120 km² [11, 12].

The region experiences a tropical wet-and-dry climate with two distinct seasons: a wet season (April–October) and a dry season (November–March).

Annual rainfall ranges between 1,200 mm and 1,800 mm, with mean annual temperatures varying from 25°C to 32°C. These climatic conditions support the Guinea Savannah vegetation, characterized by grasslands interspersed with shrubs, scattered trees, and gallery forests along rivers [4, 13].

The topography varies from low-lying plains in the west to rugged highlands in the east, particularly in Sardauna and Gashaka, where the Mambilla Plateau rises above 1,500 m [14]. The area is drained by major rivers such as the Benue and its tributaries (Donga, Taraba, and Katsina-Ala), which provide fertile alluvial soils along valleys. Upland areas are dominated by ferruginous tropical soils, which are moderately fertile but prone to erosion under intensive land use [15].

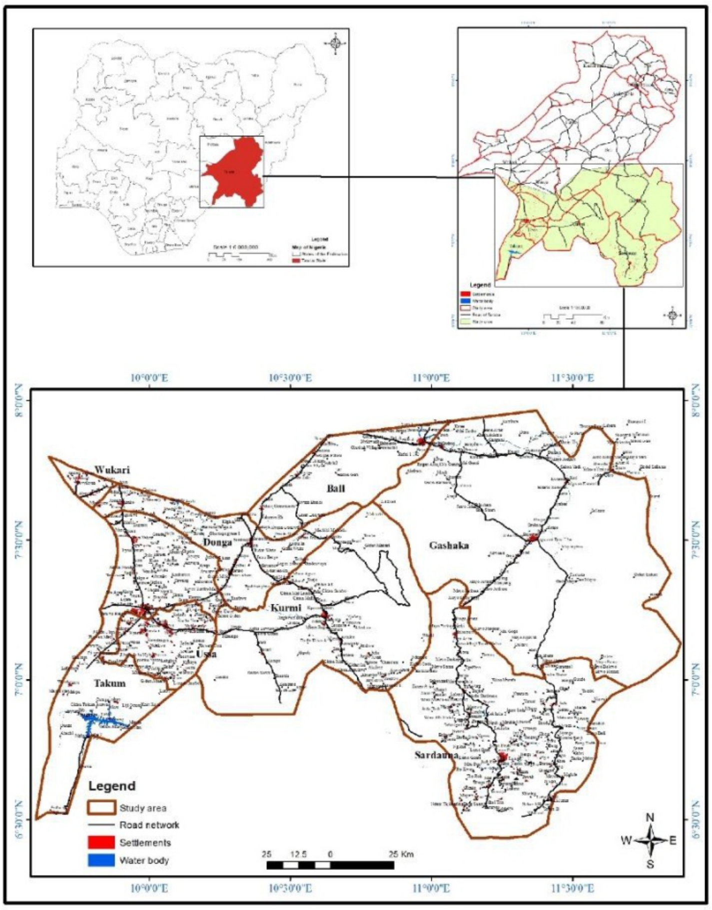

Fig. 1. Map of the Study Area

The zone is ecologically diverse, containing important forest and wildlife habitats. The Gashaka-Gumti National Park, Nigeria's largest national park, is located in this zone and harbors high biodiversity, including endangered primates and rich plant communities [16]. However, outside protected areas, vegetation has been significantly altered by human activities such as shifting cultivation, logging, fuelwood harvesting, and grazing [17].

The population is predominantly agrarian, relying on subsistence farming and livestock rearing. Major crops include yam, cassava, maize, guinea corn, and rice. Settlements are expanding, and a growing road network has increased accessibility but also accelerated land use change. Pressure from agricultural expansion, grazing, and urbanization is the primary driver of deforestation and land degradation, thereby reducing the zone's carbon sequestration potential [18]. In summary, the Southern Guinea Savannah zone of Taraba State is an ecologically significant yet vulnerable landscape, where climatic, geomorphological, and socio-economic dynamics interact to influence patterns of biomass productivity and carbon storage.

Materials and Methods

The study was carried out in the Southern Guinea Savannah agro-ecological zone of Taraba State, Nigeria. The boundary of the study area was delineated using administrative shapefiles, which were clipped to the Southern Guinea Savannah extent. All spatial datasets were projected into an equal-area coordinate system to ensure accuracy in biomass and area estimations, following standard GIS practice [15].

Multi-date Landsat imagery for 1987, 2004, 2014, and 2024 was acquired from the United States Geological Survey (USGS) archive. Cloud-free or minimal-cloud surface reflectance products from Landsat TM, ETM+, and OLI sensors were selected, with preference for images from comparable phenological periods to minimize seasonal variability. The Landsat Collection 2 Level-2 surface reflectance dataset was used to ensure consistency across epochs [20].

The images underwent standard preprocessing procedures, including radiometric calibration, atmospheric correction, cloud and shadow masking, mosaicking, and subsetting to the study area. Co-registration of the images was performed to align pixels across epochs, with registration error maintained below 0.5 pixels to reduce classification error during change detection. These steps followed established remote sensing protocols [20, 21]. To improve vegetation class separability, spectral indices such as the Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), and tasseled-cap transformations (brightness, greenness, and wetness) were generated. Auxiliary data, including slope and elevation derived from a digital elevation model (DEM), were also integrated to enhance classification accuracy [21].

Supervised classification was performed separately for each epoch using training samples derived from field surveys, historical aerial photographs, and high-resolution Google Earth imagery. The major land use/land cover (LULC) classes included dense forest, secondary forest/woodland, savannah/grassland, cropland, built-up areas, bare land, and water bodies. Classification was carried out using a supervised algorithm (e.g., Maximum Likelihood or Random Forest), followed by post-classification filtering to reduce speckle. The classification outputs were validated using independent ground-truth points and visually interpreted high-resolution imagery. Accuracy assessment employed error matrices, with overall accuracy, producer's and user's accuracies, and Kappa coefficients calculated following Congalton and Green [22].

Carbon-stock maps for each epoch were generated by multiplying AGB values by 0.5 and reclassifying the outputs into carbon density classes: low (<5.2 t C/ha), moderate (5.2–21.3 t C/ha), and high (>21.3 t C/ha). The spatial distribution and extent of each carbon class were computed, and carbon stock changes were analyzed across the four temporal epochs (1987, 2004, 2014, and 2024). Change detection was implemented using a post-classification comparison approach, which allowed the quantification of transitions between carbon classes over time and the computation of net gains and losses in carbon stocks [21].

Uncertainty was addressed by considering sources such as classification error, AGB estimation error, and the assumption of a uniform 50% biomass-to-carbon conversion. Although explicit uncertainty estimates were not quantified in this study, best practice involves propagating these errors to report confidence intervals, as recommended in international guidelines [23, 24].

All spatial analyses were conducted using standard GIS and remote sensing software environments, including ArcGIS/QGIS for spatial processing, ENVI/ERDAS or Google Earth Engine for image classification and preprocessing, and R/Python for statistical analysis.

Result of the Findings

The spatial distribution of carbon sequestration potential across the Southern Guinea Savannah of Taraba State varied markedly over the study period, as revealed by the carbon density maps generated for 1987, 2004, 2014, and 2024. Three main carbon density classes were delineated: low (<5.2 t C/ha), moderate (5.2–21.3 t C/ha), and high (>21.3 t C/ha). These maps provide a temporal perspective on the extent and dynamics of carbon storage across the landscape.

In 1987, the carbon sequestration map (Fig. 2) was dominated by moderate and high-density classes. The high carbon density areas were concentrated in the southern and central zones of the study area, corresponding largely to dense forest and woodland cover. These regions exhibited relatively continuous patches of high biomass, suggesting intact vegetation with minimal disturbance. Moderate carbon density zones were more widely distributed, covering savannah woodlands and areas with mixed tree-grass mosaics. Low-density carbon zones, which corresponded to bare land, croplands, and degraded savannah, occupied only a minor fraction of the landscape. Overall, the map indicated that the Southern Guinea Savannah was functioning as a robust carbon sink in this baseline year.

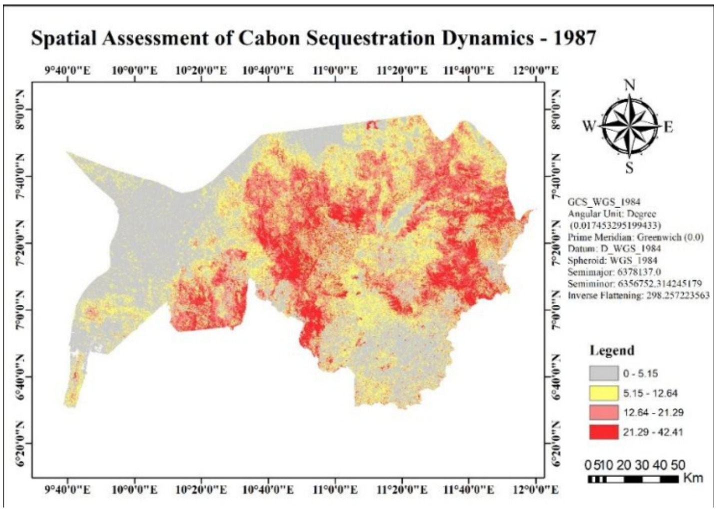

Fig. 2 Spatial Assessment of Carbon Sequestration Dynamics 1987

By 2004, the maps (Fig. 3) revealed a noticeable contraction of high carbon density areas, particularly around the peripheries of forested zones. Many of these areas transitioned into the moderate carbon class, reflecting ongoing deforestation, agricultural expansion, and fragmentation of forest cover. The spatial continuity of high-density carbon patches was disrupted, leaving more isolated fragments in the central and southern regions. The expansion of low-carbon-density zones was evident, especially in the northern and eastern portions of the study area, where cropland and settlements had expanded. This pattern suggested accelerating land use pressures, which undermined the landscape's capacity for carbon storage.

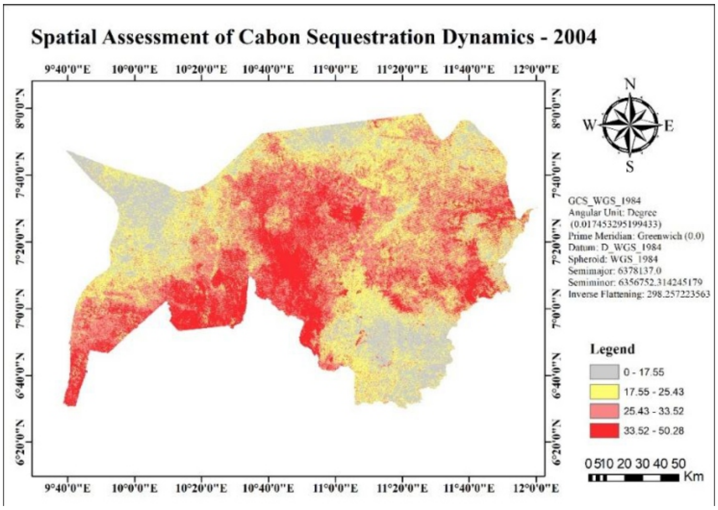

Fig. 3. Spatial Assessment of Carbon Sequestration Dynamics 2004

The 2014 carbon sequestration map (Fig. 4) showed a further intensification of these trends. High carbon density zones became increasingly scarce, confined to a few scattered patches in the southern margins and around protected areas. Moderate carbon density areas continued to shrink as more land transitioned into the low carbon category. The low-density class expanded significantly, now covering much of the northern and eastern sectors, with spatial evidence of large tracts of cropland and degraded savannah. The map highlighted a critical shift: the dominance of low carbon density across the study area, indicating a major decline in biomass carbon stocks.

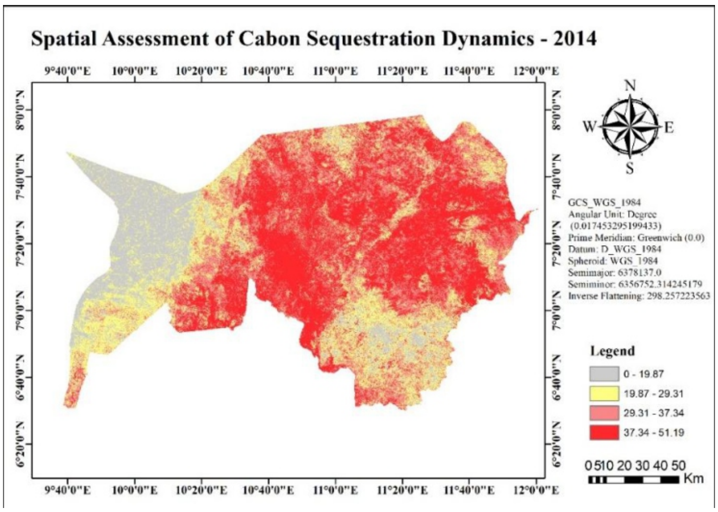

Fig. 4. Spatial Assessment of Carbon Sequestration Dynamics 2014

By 2024, the degradation trajectory reached a critical point. The carbon sequestration map (Fig. 5) was overwhelmingly dominated by the low-density class, which occupied the majority of the landscape. High carbon density areas were nearly absent, surviving only as small, isolated fragments in a few southern pockets.

Moderate carbon density zones also contracted further, representing a narrow transitional belt between the sparse high-density patches and the dominant low-density areas. The widespread expansion of low-density carbon areas illustrated the combined effects of decades of deforestation, agricultural intensification, and other anthropogenic pressures.

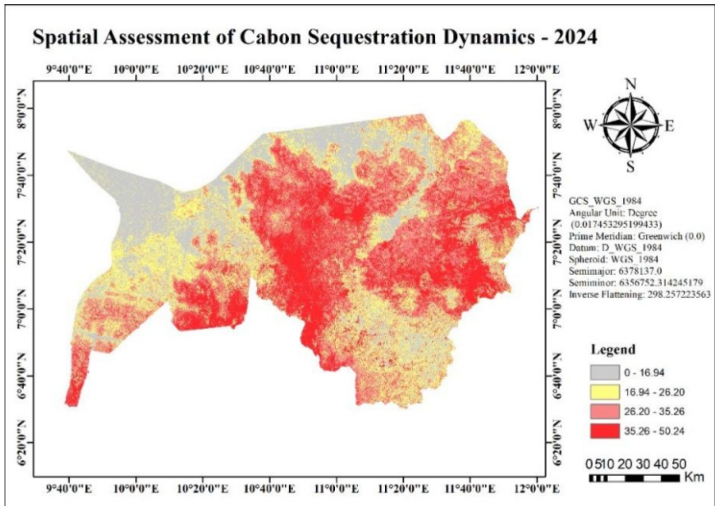

Fig. 5. Spatial Assessment of Carbon Sequestration Dynamics 2024

The temporal comparison of the four maps revealed a consistent trend of declining carbon stocks and spatial homogenization of the landscape into low carbon density. Between 1987 and 2024, there was a marked reduction in the extent of high and moderate carbon zones, accompanied by the proliferation of low carbon areas. This transformation not only reflects the loss of vegetation cover and biomass but also underscores the vulnerability of the Southern Guinea Savannah to carbon depletion. The maps thus provide compelling spatial evidence that the study area has shifted from being a significant carbon reservoir in the late 1980s to a predominantly low-carbon landscape by the mid-2020s.

These findings highlight the accelerating degradation of ecosystem carbon storage potential in Taraba's Southern Guinea Savannah and emphasize the urgent need for sustainable land management practices, reforestation programs, and conservation measures to restore and enhance carbon sequestration capacity.

Carbon Sequestration Class Coverage in the Study Area

The summary of the distribution of carbon sequestration classes in the Southern Guinea Savannah agroecological zone of Taraba State over four benchmark years - 1987, 2004, 2014, and 2024 is presented in Table 1. The carbon classes were grouped into four categories: Low (0–25.28 t C/ha), Medium (25.28–42.58 t C/ha), High (>42.58 t C/ha), and Very High. Each category is presented with the corresponding land area in square kilometers and the percentage share of the total study area (25,119.673 km^2).

Table 1: Carbon Sequestration Class Coverage in the Study Area (1987–2024)

Carbon Class	1987 Area (km^2)	1987 (%)	2004 Area (km^2)	2004 (%)	2014 Area (km^2)	2014 (%)	2024 Area (km^2)	2024 (%)	Net Change (1987–2024)	% Change (1987–2024)
Low (0–25.28)	9249.73285	36.82266425	4412.503525	17.56592741	3840.330325	15.28813821	4862.886925	19.3588783	−4,386.85	−47.43 %
Medium (25.28–42.58)	7299.50665	29.05892386	7764.874825	30.91152829	5231.513425	20.82635958	6382.368625	25.40784916	−917.14	−12.57 %
High (>42.58)	5367.46405	21.36757135	7843.923625	31.2262171	7006.929925	27.89419243	7766.226625	30.91690973	+2,398.76	+44.70 %
Very High	3202.96945	12.75084055	5098.371025	20.29632721	9040.899325	35.99130978	6108.190825	24.31636282	+2,905.22	+90.69 %
Total	25119.673	**100%**	25119.673	**100%**	25119.673	**100%**	25119.673	**100%**	0	0 %

In 1987, the largest proportion of the landscape was occupied by the Low class, covering 9,249.73 km^2 (36.8%). This was followed by the Medium class with 7,299.51 km^2 (29.1%), the High class with 5,367.46 km^2 (21.4%), and the Very High class with 3,202.97 km^2 (12.8%). This initial distribution indicates that although low-carbon areas were widespread, substantial portions of the landscape still retained medium to very high carbon storage potential.

By 2004, significant shifts occurred. The Low class decreased to 4,412.50 km^2 (17.6%), reflecting land transitions into higher carbon categories, particularly the High and Very High classes, which increased to 7,843.92 km^2 (31.2%) and 5,098.37 km^2 (20.3%), respectively. The Medium class also rose slightly to 7,764.87 km^2 (30.9%). This suggests that between 1987 and 2004, parts of the landscape underwent regeneration or accumulation of biomass, leading to improvements in carbon sequestration in some zones.

However, the 2014 data reveal a reversal of this gain. The Low class further contracted to 3,840.33 km^2 (15.3%), but the most dramatic change was in the Very High class, which surged to 9,040.90 km^2 (36.0%), making it the dominant category. The High class declined to 7,006.93 km^2 (27.9%), while the Medium class reduced sharply to 5,231.51 km^2 (20.8%). This pattern indicates intensification of carbon stock polarization, with parts of the landscape accumulating very high biomass, while medium-level stocks were lost.

By 2024, the distribution shifted once more. The Low class increased again to 4,862.89 km^2 (19.4%), signaling renewed expansion of low-carbon areas, possibly due to land degradation or deforestation. The Medium class grew to 6,382.37 km^2 (25.4%), while the High class also expanded slightly to 7,766.23 km^2 (30.9%). Conversely, the Very High class declined to 6,108.19 km^2 (24.3%), indicating losses from the peak observed in 2014. This mixed pattern reflects the combined effects of land cover changes areas of degradation reducing carbon stocks, while others retained or transitioned into medium and high carbon categories.

Overall, Table 1 demonstrates that carbon sequestration in the Southern Guinea Savannah has been highly dynamic over the past four decades. The landscape transitioned from low dominance in 1987 to substantial increases in Very High carbon stocks by 2014, before experiencing a decline in 2024. These fluctuations highlight the influence of both natural processes and human-induced land cover changes on carbon storage capacity in the region.

One-way ANOVA for Carbon Sequestration Across Years

Table 2 presents the results of a one-way Analysis of Variance (ANOVA) used to test whether there were statistically significant differences in mean carbon sequestration across the study years. The "Between Groups" sum of squares was 8,901.65 with 2 degrees of freedom, yielding a mean square value of 4,450.82. The "Within Groups" sum of squares was 318,261.72 with 3,513 degrees of freedom, producing a mean square of 90.58. The computed F-statistic was 49.129, and the associated p-value (Sig.) was 0.000, which is less than the conventional threshold of 0.05.

Table 2: One-way ANOVA for Carbon Sequestration Across Years

Variable	Source	Sum of Squares	df	Mean Square	F	Sig. (p)
Carbon Sequestration	Between Groups	8,901.65	2	4,450.82	49.129	0.000
	Within Groups	318,261.72	3513	90.58		
	Total	327,163.37	3515			

This result indicates that the differences in mean carbon sequestration across years were highly statistically significant. In practical terms, it confirms that the temporal changes observed in the distribution of carbon classes from 1987 to 2024 were not due to random variation but instead reflect systematic and meaningful shifts in carbon sequestration dynamics. These findings reinforce the patterns seen in the carbon maps and tables, where declines in medium and high carbon classes and expansions of low carbon areas were evident. The ANOVA result, therefore, validates that carbon sequestration capacity in the Southern Guinea Savannah has undergone significant change over the study period.

Tukey's HSD Post Hoc Test for Carbon Sequestration

The results of mean comparisons for carbon sequestration across the study years reveal patterns that mirror those of biomass, highlighting the intrinsic linkage between the two variables. A statistically significant increase in carbon sequestration was observed between 2004 and 2014 (Mean Difference = 2.92, $p < 0.001$), reflecting a decade of enhanced biomass accumulation and improved ecosystem carbon storage. In contrast, the difference between 2004 and 2024 was not statistically significant (Mean Difference = −0.78, $p = 0.116$), suggesting that by 2024, carbon sequestration levels had regressed to values similar to those of 2004. The most substantial decline occurred between 2014 and 2024, with a highly significant reduction (Mean Difference = −3.70, $p < 0.001$), confirming that forest degradation and deforestation during this period drastically eroded the ecosystem's capacity for carbon storage and climate regulation.

Table 3: Tukey's HSD Post Hoc Test for Carbon Sequestration across Years

Comparison	Mean Difference	p-value	95% CI (Lower–Upper)	Significant (p<0.05)
Carbon_2004 vs 2014	2.9171	0.000	1.9952 – 3.8390	Yes
Carbon_2004 vs 2024	-0.7800	0.1164	-1.7019 – 0.1420	No
Carbon_2014 vs 2024	-3.6970	0.000	-4.6190 – -2.7751	Yes

Tukey's HSD post hoc test results (Table 3) provide further detail on the temporal trajectory of carbon sequestration. Between 2004 and 2014, the test confirmed a statistically significant increase in mean carbon stocks (Mean Difference = 2.92, $p < 0.001$; 95% CI = 1.99–3.84), highlighting a decade of carbon gains, likely attributable to vegetation recovery or favorable climatic conditions. However, the comparison between 2004 and 2024 showed no significant difference (Mean Difference = –0.78, $p = 0.116$), indicating that the gains observed in 2014 were not sustained and that carbon levels had effectively returned to 2004 values. The sharpest decline was detected between 2014 and 2024, with a significant reduction of –3.70 ($p < 0.001$; 95% CI = –4.62 to –2.78), reflecting severe forest degradation and biomass loss during this period.

The combined results of Tables 2 and 3 show that carbon sequestration in the Southern Guinea Savannah agro-ecological zone followed a boom-and-bust trajectory: a peak in 2014 followed by a steep decline to 2024 levels comparable with those of 2004. This cyclical pattern indicates that while temporary recovery of vegetation is possible, unsustainable land use practices, including deforestation, agricultural expansion, and logging, undermine long-term carbon storage capacity. From an ecosystem services perspective, the findings emphasize that the ability of the Southern Guinea Savannah to provide carbon sequestration, biomass productivity, and climate regulation is being progressively eroded. These results highlight the urgent need for sustainable forest management, afforestation, reforestation, and community-based conservation interventions to safeguard and restore the region's carbon sink functions.

Carbon Sequestration Across the Years

The boxplot of carbon sequestration across 2004, 2014, and 2024 (Fig. 6) reflects temporal shifts in the ecosystem's carbon storage capacity, closely paralleling the biomass trend. In 2004, the median carbon stock was 15.96 t C/ha, with most observations ranging from 11.03 to 22.11 t C/ha. The distribution was relatively compact, indicating relatively uniform carbon storage across much of the study area, although a small number of sites recorded zero values corresponding to bare or non-vegetated land.

By 2014, the carbon storage profile improved markedly. The median value increased to 17.90 t C/ha, while the interquartile range widened, suggesting greater variability among sites. Notably, several high outliers exceeded 45 t C/ha, showing that certain areas accumulated substantial carbon reserves, likely due to localized vegetation recovery or favorable conditions. This upward shift was confirmed statistically by Tukey's HSD test, which identified a significant increase in carbon stocks between 2004 and 2014 (Mean Difference = +2.92, $p < 0.001$).

In 2024, the trend reversed sharply. The median carbon stock declined to 14.84 t C/ha, slightly below the 2004 baseline. Furthermore, 26 observations recorded zero values, indicating a rise in degraded or deforested sites with no capacity to store carbon. This decline demonstrates that the gains observed in 2014 were not sustained and, in some cases, conditions deteriorated further than the earlier baseline.

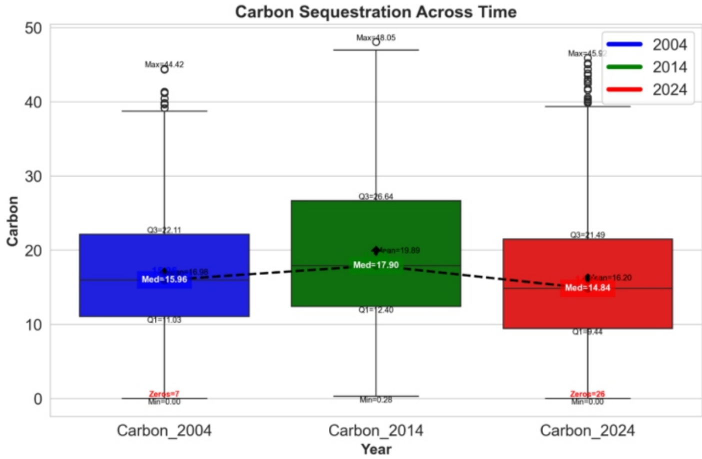

Figure 6: Carbon Sequestration Across the Years

Overall, the boxplot (Fig. 6) provides compelling evidence of a boom-and-bust trajectory in carbon sequestration across the Southern Guinea Savannah agroecological zone of Taraba State. While carbon storage peaked in 2014, subsequent degradation and land use pressures drove levels back to or below 2004 conditions by 2024. These findings highlight the fragility of vegetation-driven carbon storage and reinforce the conclusion that ongoing deforestation and land degradation significantly undermine the ecosystem's role as a carbon sink.

The combined interpretation of the area-based carbon class coverage (Table 1), the statistical analyses (Tables 2 and 3), and the boxplot distribution (Figure 6) provides a comprehensive picture of carbon sequestration dynamics in the Southern Guinea Savannah of Taraba State between 1987 and 2024. Table 1 shows that in 1987 the landscape was distributed across all carbon density classes, with Low carbon areas occupying 36.8% of the land, while Medium, High, and Very High classes together accounted for over 60% of the study area. This distribution indicated a relatively balanced ecosystem with substantial carbon storage potential. By 2004, the Very High class expanded to 20.3% and the High class to 31.2%, suggesting localized improvements in biomass accumulation. However, the situation shifted dramatically by 2014, when the Very High class peaked at 36.0% while Medium stocks dropped to 20.8%, reflecting strong polarization—some areas accumulating substantial carbon, while others lost intermediate storage capacity. By 2024, both the Very High and Medium classes declined (24.3% and 25.4%, respectively), while the Low class expanded again to 19.4%, showing renewed degradation and carbon loss.

The statistical results in Tables 2 and 3 confirm that these area shifts represent significant temporal changes. ANOVA revealed highly significant differences in mean carbon sequestration across years, while Tukey's HSD post hoc tests highlighted the trajectory: a significant increase from 2004 to 2014 (+2.92, $p < 0.001$), no significant difference between 2004 and 2024 (–0.78, $p = 0.116$), and a sharp decline from 2014 to 2024 (–3.70, $p < 0.001$). These findings demonstrate that while carbon stocks improved during 2004–2014, the gains were temporary and erased in the following decade, returning the system to 2004 levels.

Figure 6 complements these findings visually. The boxplot shows the 2014 peak in median carbon stocks (17.90 t C/ha) with wider variability and high outliers exceeding 45 t C/ha, followed by a decline in 2024 to a median of 14.84 t C/ha with 26 zero-value observations, indicating degraded or deforested patches. This reinforces the evidence from Table 1 of expanding Low-carbon areas and from Tables 3–4 of significant statistical decline.

Taken together, the results present a consistent boom-and-bust trajectory: initial balance in 1987, localized improvement up to a peak in 2014, and subsequent decline by 2024. The convergence of spatial, statistical, and visual evidence underscores that unsustainable land use and deforestation are driving long-term carbon losses, eroding the Southern Guinea Savannah's capacity to act as an effective carbon sink.

Discussion

The findings of this study reveal a distinctive "boom-and-bust" trajectory of carbon sequestration in the Southern Guinea Savannah of Taraba State: a significant increase in carbon storage between 2004 and 2014, followed by a sharp decline between 2014 and 2024. This trajectory aligns with some regional studies while diverging from others, reflecting both methodological and contextual differences.

The decline in carbon stocks observed between 2014 and 2024 is consistent with the work of Adenle et al [25], who reported widespread land degradation across the Nigerian Guinea Savannah using NDVI evidence. They attributed this degradation to human-induced factors, including deforestation and agricultural expansion, which mirror the drivers identified in our study. Similarly, Akinyemi et al [18] documented extensive cropland and settlement expansion across Nigeria's agroecological zones at the expense of tree cover and wetlands. Their findings reinforce the evidence from Taraba that anthropogenic land use pressures are central to the observed reduction in carbon sequestration capacity.

At the local scale, Bunde [17] highlighted the threats facing woody plant species in Taraba State, noting pressures from fuelwood collection, grazing, and unregulated logging. These localized drivers help to explain the sharp decline in carbon storage observed in the present study between 2014 and 2024, as they directly undermine aboveground biomass and soil carbon reserves.

On the other hand, the temporary increase in carbon stocks recorded between 2004 and 2014 in this study agrees with the observations of Bera et al [26], who found that land use and land cover changes in tropical landscapes can sometimes lead to short-term carbon gains, particularly where secondary succession or localized protection allows vegetation to recover. Abreu et al [27] similarly noted that suppression of disturbances such as fire and grazing in tropical savannas can lead to temporary biomass accumulation, although this often comes with ecological trade-offs. These studies support the interpretation that the rise in carbon storage up to 2014 in Taraba may have been due to localized vegetation recovery or favourable climatic conditions, rather than systemic improvements in land management.

However, the findings of this study diverge from broader, large-scale analyses such as those of Potapov et al [28], who reported a more monotonic global decline in forest cover and associated carbon stocks from 2000 to 2020. The difference can be attributed to scale and methodology. While continental-scale studies average data over vast areas, masking localized recovery, finer-scale analyses such as the present one can detect temporary increases in carbon storage within specific landscapes. Methodological choices, including the use of stratified biomass classes and the IPCC conversion factor, may also contribute to these differences.

Climatic influences also help to contextualize the results. The Intergovernmental Panel on Climate Change [29] emphasized that rising temperatures and shifting rainfall patterns accelerate vegetation stress and soil carbon loss. Asa and Zemba [4] similarly documented delayed rainfall onset and increasing temperatures across Taraba State, which shorten growing seasons and heighten moisture stress. These climatic factors likely exacerbated the human-driven degradation processes that contributed to the carbon sequestration decline observed between 2014 and 2024.

In summary, the results of this study agree with local and regional findings that highlight land use pressures and climate variability as primary drivers of carbon loss [18, 17, 25,], and they partially agree with studies that document short-term carbon gains from localized vegetation recovery [26, 27]. The divergence from large-scale monotonic decline studies [28] underscores the importance of scale and methodology in assessing carbon dynamics. The overall trajectory points to the fragility of carbon storage in the Southern Guinea Savannah and emphasizes the urgent need for sustainable forest management, reforestation, and community-based conservation interventions to safeguard the region's role as a carbon sink.

Conclusion

This study assessed carbon sequestration dynamics in the Southern Guinea Savannah of Taraba State over nearly four decades (1987–2024). The findings revealed a fluctuating trajectory, with carbon stocks peaking in 2014 before declining sharply by 2024, returning to levels comparable to those of 2004. These results highlight the combined influence of land use change, deforestation, agricultural expansion, and climate variability in shaping carbon storage patterns. The expansion of low-carbon areas and the loss of high-carbon zones underscore the vulnerability of savanna ecosystems to unsustainable resource use. While temporary gains indicate potential for recovery under favorable conditions, the subsequent decline emphasizes the fragility of these gains without long-term management interventions. The study concludes that safeguarding the carbon sink function of the Southern Guinea Savannah requires integrated approaches, including sustainable land management, forest conservation, afforestation, and community-driven practices to enhance resilience and support Nigeria's broader climate change mitigation goals.

Recommendations

Based on the findings of this study, the following recommendations are made:

i. Promote sustainable forest management – Strengthen enforcement of forestry regulations to reduce deforestation and degradation. This includes monitoring illegal logging, establishing fuelwood alternatives, and enhancing forest reserves to safeguard remaining high-carbon zones.

ii. Implement afforestation and reforestation programs – Launch large-scale tree planting using native and climate-resilient species to rehabilitate degraded lands. Such programs should target riparian areas, bare lands, and abandoned farms to boost long-term carbon sequestration.

iii. Support community-based conservation – Involve local communities in forest governance through participatory management frameworks. Providing incentives such as alternative livelihoods, ecotourism, and benefit-sharing mechanisms will foster stewardship of forest resources.

iv. Encourage sustainable agricultural practices – Promote agroforestry, crop rotation, controlled grazing, and conservation tillage to improve soil health, reduce land degradation, and enhance soil organic carbon retention while supporting food security.

v. Strengthen climate adaptation policies – Integrate climate variability and projections into land-use planning to enhance ecosystem resilience. Developing early warning systems for drought and fire, alongside climate-smart land management, will reduce vulnerability to climate change impacts.

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