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SPECIAL ISSUE: CELEBRATING 20 YEARS OF GEOGRAPHY IN KADUNA STATE UNIVERSITY - ADVANCES AND FRONTIERS IN GEOGRAPHY

Soil Organic Carbon Stock and Sequestration Potential in Southern Guinea Savanna Ecological Zone, Nigeria

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ABSTRACT

Carbon sequestration in soils has a huge potential to decrease the rate of CO2 emission to the atmosphere. However, little is known about Soil Organic Carbon (SOC) stock and fluxes in savannas. This study quantified the SOC of major plant communities in the southern guinea savanna ecological zone of Nigeria to determine their carbon sequestration potential for climate change mitigation. Field and laboratory procedures were employed to estimate carbon stock. Soil samples were collected by resampling from 40 permanent sampling plots for the years 2013, 2017, and 2021, respectively. Eighty composite soil samples were taken at two depths (0-15cm and 15-30cm). SOC concentration was estimated in the laboratory using the wet-oxidation Walkley-Black method. Findings revealed that between 2013 and 2021, the mean bulk density at 0–15 cm increased from 1.29 to 1.38 g cm-3, while at 15-30cm depth ranged from 1.30 to 1.36 g cm-3, signifying an increasing trend of soil compaction. Conversely, the mean SOC at 0–15 cm decreased from 20.11 to 14.06 Mg ha-1 while 15-30cm ranged from 15.84 to 11.92 Mg ha-1, implying carbon loss. The mean SOC concentration was mostly higher in the 0-15 cm layer than in the 15-30 cm layer. Savanna Woodland recorded the highest SOC (23.41 Mg ha-1) in 2013, while the Recent fallow land recorded the lowest (7.25 Mg ha-1) in 2021. Between 2013 and 2021, carbon emissions occurred at an annual loss rate of 8.87 Mg ha-1 yr-1. It was concluded that the restoration of the various plant communities has the potential to sequester about 79.84 Mg ha-1 of SOC at an annual rate of 8.87 Mg ha-1, which will provide effective climate change mitigation. This study recommends sustainable management practices for soil carbon sequestration, such as forest protection, fire management, afforestation, the use of organic fertilizers, and soil amendments.

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1 Introduction

Tropical Savannas have been recognized as important areas of interest in climate change mitigation and adaptation studies due to their vast spatial extent, significant biomass productivity, poor land management, and high vulnerability to climate change (Janowiak et al., 2017; Jibrin, 2017; Jibrin et al., 2018; Zhou et al., 2023; Jorge et al., 2025). Savannas are characterized by a mixture of coexisting trees, shrubs, and grasses, but range from grasslands where trees are virtually absent to more forest-like woodland ecosystems where trees are dominant (Bhardwaj, 2019). The savanna ecological landscapes are significant sources and sinks of carbon, owing to the high rate of deforestation, forest degradation, wildfires, and resultant soil degradation (Smith, 2012; Odunze et al., 2017; Intergovernmental Panel on Climate Change [IPCC], 2019a; Grieco et al., 2024). Soils are critical for global biogeochemical cycles that include the carbon, nutrient, and hydrological cycles (Food and Agriculture Organization [FAO] & Intergovernmental Technical Panel on Soils [ITPS], 2015; IPCC, 2019b; Nikodemus et al., 2022).

There is a strong interest in stabilizing the atmospheric abundance of CO2 and other GHGs to mitigate the risks of climate change. Due to the impact on radiative forcing, there is increasing emphasis on identifying strategies that will reduce the rate of enrichment of atmospheric CO2 by offsetting anthropogenic emissions (IPCC, 2019a; Adekiya et al., 2023; Singh et al., 2024; Jorge et al., 2025). The focus, therefore, is on the sequestration of CO2 from the atmosphere or point sources. Atmospheric enrichment of GHGs can be moderated by either reducing anthropogenic emissions or sequestering Carbon in plant biomass or the soil (Anokye et al., 2021; Just et al., 2023).

Carbon sequestration is the process of removal or capture and long-term storage of atmospheric carbon dioxide to mitigate global warming and avoid the dangerous impacts of climate change (Lal, 2004; Smith, 2012; Lal, 2015; Shuaib et al., 2025; Okiemute, 2025). Being the largest pool of terrestrial carbon stock, Soil Organic Carbon (SOC) can be a sink or source of atmospheric CO2 (Castellano et al., 2022). Therefore, mitigation of climate change consequences requires a clear understanding of the spatial distribution of SOC (IPCC, 2014; Abdullahi et al., 2018; Rodrigues et al., 2023; Omotoso & Omotayo, 2024). Moreover, Carbon sequestration in soils, and other terrestrial ecosystems, have both mitigation and adaptation implications. The mitigation impacts of

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innovative agricultural systems accrue from the net reduction in GHG emissions (Smith, 2012; IPCC, 2019b; IPCC, 2021). The adaptation impacts of adopting improved soils and crop management systems are based on the reduction of the adverse effects of projected climate change (Smith, 2012; IPCC, 2019b; IPCC, 2021; Rodrigues et al., 2023). Soil is an important natural sink for sequestering atmospheric CO2, and its role in reducing the rate of enrichment of atmospheric CO2 cannot be overemphasized. However, despite a strong inter-dependence between climate and soil quality (Akpa et al., 2016; Pham et al., 2018; Mesele & Huising, 2024), the role of SOC dynamics in the historic increase in atmospheric CO2, and its strategic importance in decreasing the future rate of CO2 emission are not adequately understood in the developing countries (Bessah et al., 2016; Traoré et al., 2020; Nwabueze et al., 2021), such as Nigeria.

One of the most pressing questions concerning future climate change is how the spatial and temporal distribution of carbon pools and fluxes will be managed (FAO, 2010). These problems are acute in tropical savannas given the limited available data to parameterize dynamic vegetation models to simulate climate change impacts (IPCC, 2014; Rodrigues et al., 2023; Gonçalves et al., 2024). This indicates an urgent need to understand the various processes that regulate the uptake and release of CO2 and other greenhouse gases by savannas and analyze their dependence on key environmental drivers. Such studies are critical to predict the impacts of future climate change on savanna carbon storage (Smith, 2012; Janowiak et al., 2017; IPCC, 2019a; Gonçalves et al., 2024) for better land management, and to inform policy aimed at stabilizing atmospheric CO2 concentration, and combat climate change (FAO & ITPS, 2021; IPCC, 2021; Kadiri et al., 2023). Further, the available data on SOC in the literature are mostly confined to the top (0–15 cm) soil layer and often without considering soil bulk density (Lal, 2015). This study is aimed at quantifying the SOC of major plant communities in the southern guinea savanna ecological zone of Nigeria, to determine their carbon sequestration potential for climate change mitigation. Restoring degraded soils and ecosystems is a strategy with multiple benefits for water quality, biomass productivity, and reducing net CO2 emissions, especially the degraded land in the savanna with the potential for afforestation and soil quality enhancement.

2 Materials and Methods

2.1 Study Area

The study was carried out in the southern guinea savanna ecological zone, situated in Lapai Local Government Area of Niger State, Nigeria. The study area location (Figure 1) lies between latitude 8° 39' to 8° 50' North and longitude 6° 34' to 6° 46' East (Forest Management Evaluation and Co-ordinating Unit [FORMECU], 1994). The study area is found within the tropical hinterland climatic belt of Nigeria, characterized by alternating wet and dry seasons coded as 'Aw' by Köppen's classification. The mean annual rainfall is about 1,400 mm with a mean annual temperature of about 28 °C (Nigeria Meteorological Agency [NiMet], 2023). The geology of the study area is made up of Cretaceous sedimentary rocks underlain by the Precambrian basement complex rocks (FORMECU, 1994). With an average altitude of 400 meters above sea level, the topography is gently undulating, sloping generally towards different directions in different locations. Based on FAO soil classification, the major soil groups found in the Guinea Savanna are Luvisol, Ferralsols, Acrisols, Lithosols, and Vertisols (International Institute of Tropical Agriculture [IITA], 1992). The soils largely belong to ferruginous tropical soils. In some depression areas and valley bottom positions, hydromorphic soils are found; whereas those around the inselbergs and other residual hills, and at the bed of rivers, are weakly developed soil (Areola, 1978; Jaiyeoba & Essoka, 2006). The study area lies within the southern Guinea savanna zone classified as woodland savanna vegetation with the understory dominated by annual grasses (Keay, 1953; Jaiyeoba & Essoka, 2006).

2.2 Sample Size and Sampling Technique

Fieldwork: In line with Ellert et al. (2008), a preliminary soil sampling survey was conducted in 2013, when fifteen soil samples were randomly selected over the entire study area, SOC content was analyzed in the laboratory, and statistical variables were derived as presented in Table 1.

Table 1: Preliminary soil sampling

Sample Mean ($\bar{x}$)	Sample Variance (s)	Desired Accuracy (d)	Confidence Level	t-value
19g/kg	6 g/kg	10%	95%	2

The required sample size was calculated using Equation (1), as described in Ellert et al. (2008):

$$n_{req} = \frac{t^2 \times s^2}{(d \times \bar{x})^2} \quad (1)$$

Where:
n_{req} is the required number of samples,
t is the Student's t-value, at a 95% confidence level,
s is the sample variance,
d is the required accuracy at 0.10,
$\bar{x}$ is the arithmetic mean value of the sampled parameter.

$$n_{req} = \frac{2^2 \times 6^2}{(0.10 \times 19)^2} = 39.89$$

Thus, the sample size was calculated to be 40 sample plots.

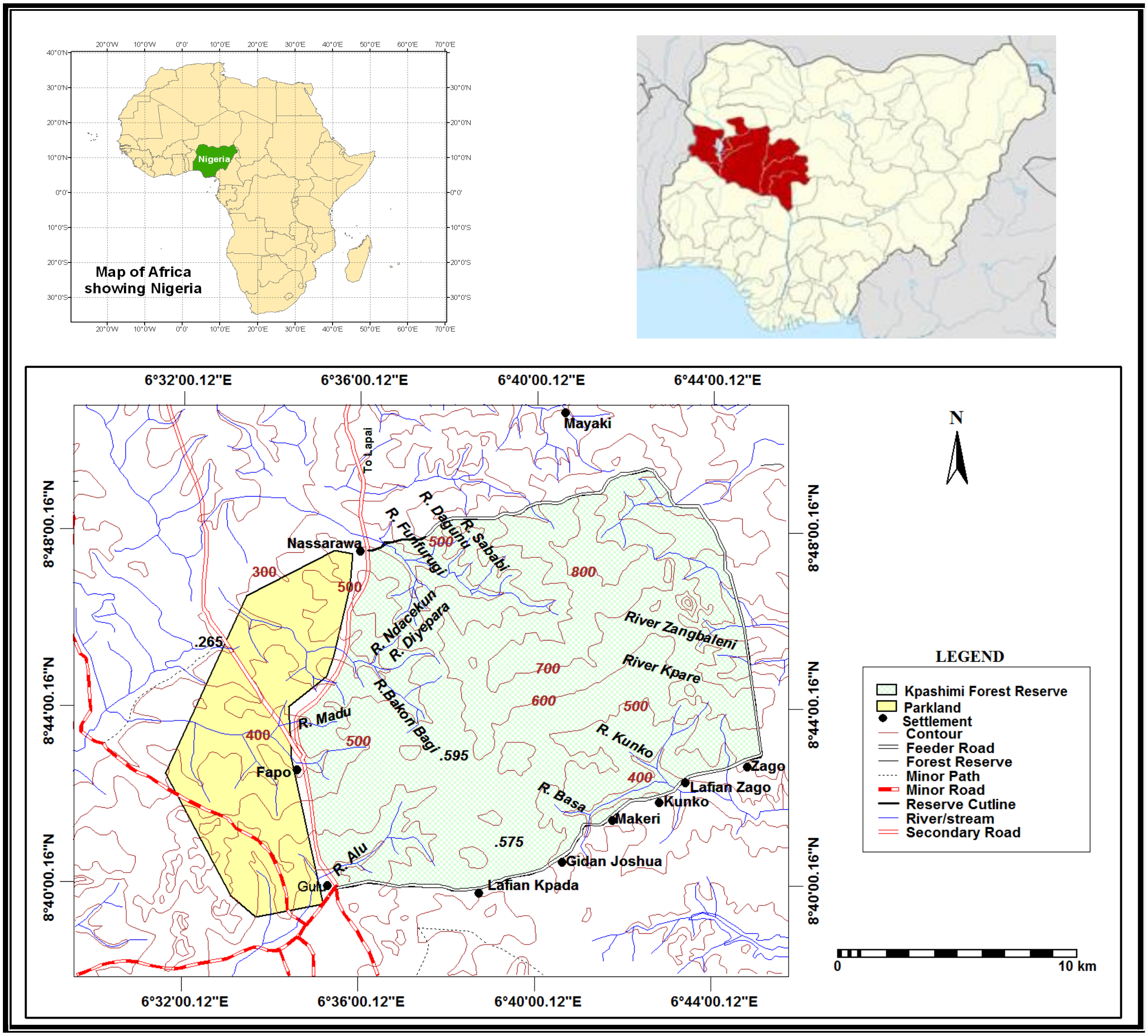

Figure 1: Location of Kpashimi Forest Reserve and Parkland Area in Niger State, Nigeria

The resampling strategy method by Lawrence et al. (2016) was adopted for monitoring soil organic carbon (SOC) stocks over successive campaigns in the study area. The rationale for the resampling strategy is to revisit and resample the same locations to minimize spatial variability and maximize the detection of actual changes over time. This approach is often integrated within a broader stratified random sampling design to ensure comprehensive coverage of the eight plant communities. The original sampling points were accurately geo-referenced by marking the locations' coordinates and natural landmark features, so that the exact locations can be revisited in subsequent campaigns. The same sampling method (e.g., probe type, depth intervals, composite sampling procedure) used in the baseline survey was used in all successive campaigns to ensure data comparability. Standard field procedures were employed to estimate carbon stock in eight selected plant communities, including Savanna Woodland, Riparian Forest, Tree Savanna, Scrubland, Grassland, Agroforestry, Old Fallow Land, and Recent Fallow Land. Five sample plots of 20 × 20 m² were randomly selected by the zigzag transect technique in each of the plant communities. The coordinates of the plots were recorded and used for each of the years 2013, 2017, and 2021. Within each sample plot, soils were collected from four corners and in the centre of the square plot at two depth classes, 0–15 and 15–30 cm, respectively. The five sub-samples in each plot were mixed thoroughly, and a composite sample was obtained for each depth class. A total of 80 samples (5 plots × 8 Plant communities × 2 depths) were collected for SOC estimation. Also, at each of the 40 plots, two undisturbed core sample was collected for the two depths (0–15 and 15–30 cm, respectively, making 2 samples per plot, summing up to 80 undisturbed core samples, for soil bulk density (Db) measurements; using a soil core ring of volume 98.2 cm^3.

Laboratory Analysis: In the laboratory, the composite soil samples were mixed thoroughly, air-dried, crushed, passed through a 2 mm sieve, and analyzed for each depth. Composite samples were analyzed through the Walkley and Black method with recovery factors of 77%. Soil bulk density was determined by the dry weight core method by oven drying the soils at 105 ºC for 24 hours. The results of the laboratory analysis were multiplied by a correction factor of approximately 1.29 to 1.30 to estimate the total organic carbon (TOC) content. This adjustment accounts for the incomplete oxidation of organic carbon that typically occurs with the Walkley-Black wet combustion method (FAO - GLOSOLAN [Global Soil Laboratory Network], 2019). The soil organic carbon of each plot was estimated by multiplying corresponding values of fine bulk density and SOC content using Equation (2) (IPCC 2003).

$$\boldsymbol{SOC} = [\boldsymbol{SOC}] \times \boldsymbol{BD} \times \boldsymbol{Depth} \times \mathbf{10} \quad (2)$$

Where:
SOC= soil organic carbon Megagram per hectare (Mg ha^{-1})
[SOC]= the concentration of soil organic carbon in a given soil mass (g C/kg soil sample)
BD= bulk density, the soil mass per sample volume (Mg m^{-3})
Depth= the depth of the soil sample in meters (m)

2.3 Data Analysis

Three datasets were collected for the years 2013, 2017, and 2021. The data obtained for the SOC was analysed using the stock change method by calculating the rate of change in SOC stock (Mg C ha^{-1} yr^{-1}) between the years of sampling over time, using Equation 3. Thereafter, Statistical Mean and Standard Deviation values were calculated using MS-Excel 2020 software package.

$$\boldsymbol{\Delta C} = \sum(\boldsymbol{Ct_2} - \boldsymbol{Ct_1}) / (\boldsymbol{t_2} - \boldsymbol{t_1}) \quad (3)$$

Where:
C = carbon stock change, tonnes C per year
Ct1 = carbon stock at time t_1, tonnes C
Ct2 = carbon stock at time t_2, tonnes C

3 Results and Discussion

3.1 Soil Organic Carbon Stock

Soil Organic Carbon Stock varied across the plant communities evaluated in the study area over the period under investigation, as presented in Table 2. Between 2013 and 2021, the mean bulk density at 0–15 cm increased from 1.29 to 1.38 g cm^{-3} while 15-30cm ranged from 1.30 to1.36 g cm^{-3}. Conversely, the mean SOC at 0–15 cm depth decreased from 20.11 to 14.06 Mg ha^{-1}, while 15-30cm depth ranged from 15.84 to 11.92 Mg ha^{-1}. By implication, the study area recorded increasing soil compaction with corresponding carbon loss.

Table 2: Soil Organic Carbon Stock of Plant Communities

Plant Communities	Db (g cm^{-3})	SOC (%)	SOC (Mg ha^{-1})	Db (g cm^{-3})	SOC (%)	SOC (Mg ha^{-1})
		0-15 cm			15-30 cm	
2013						
Savanna woodland	1.23	1.90	23.41	1.18	1.75	20.65
Riparian Forest	1.21	1.68	20.41	1.18	1.60	18.86
Tree Savanna	1.21	1.80	21.71	1.16	1.44	16.70
Scrubland	1.22	1.54	18.73	1.17	1.47	17.20
Grassland	1.22	1.41	17.23	1.28	1.42	18.23
Agroforestry	1.44	1.56	22.47	1.52	0.77	11.77
Old fallow land	1.39	1.39	19.40	1.46	0.79	11.57
Recent fallow land	1.39	1.26	17.54	1.47	0.80	11.77
Mean ±Std. Dev.	1.29		20.11±2.28	1.30		15.84±3.62
2017						
Savanna woodland	1.21	1.70	20.57	1.28	1.75	22.37
Riparian Forest	1.28	1.98	25.40	1.28	1.60	20.45
Tree Savanna	1.30	1.51	19.58	1.28	1.00	12.76
Scrubland	1.29	1.52	19.61	1.27	1.17	14.86
Grassland	1.31	1.40	18.34	1.28	1.00	12.80
Agroforestry	1.44	1.56	22.47	1.52	0.77	11.77
Old fallow land	1.39	1.04	14.48	1.46	0.69	10.10
Recent fallow land	1.49	1.00	14.90	1.47	0.42	6.17
Mean ±Std. Dev.	1.34		19.42±3.63	1.36		13.91±5.30
2021						
Savanna woodland	1.32	1.10	14.52	1.28	1.35	17.25
Riparian Forest	1.21	1.12	13.57	1.28	1.38	17.66
Tree Savanna	1.36	1.13	15.37	1.28	1.14	14.55
Scrubland	1.31	1.04	13.62	1.27	1.17	14.86
Grassland	1.32	1.04	13.73	1.28	0.64	8.19
Agroforestry	1.44	1.06	15.31	1.52	0.52	7.92
Old fallow land	1.42	0.92	13.06	1.48	0.49	7.63
Recent fallow land	1.64	0.81	13.28	1.47	0.52	7.25
Mean ±Std. Dev.	1.38		14.06±0.89	1.36		11.92±4.58

Generally, it was observed that Carbon stock decreased with an increase in depth because SOC values were mostly higher in the 0-15 cm (topsoil) than in the 15-30 cm. In 2013 and 2021, Savanna Woodland recorded the highest SOC of 23.41 Mg ha^{-1} in 2013, while the Recent fallow land recorded the lowest SOC of 7.25 Mg ha^{-1} in 2021. This difference among plant communities could be attributed to differences in the proportion of SOC contributed by the organic matter turnover of the various vegetation types (Obalum et al. 2012; Zhang & Shao, 2014; Tao & Rogers, 2019; Odebiri et al., 2024). It could be observed that while Soil bulk density increased over the years, the SOC Mg ha^{-1} decreased. This can be attributed to persistent soil degradation over the years (Anikwe, 2010; Ibrahim & Idoga, 2013; IPCC, 2019a). Most soils under the managed ecosystems contain a lower SOC pool than their counterparts under natural ecosystems owing to the depletion of the SOC pool in cultivated soils (Ndor & Iorkua, 2013; Nwaogu et al., 2018; Abdulkadir et al., 2021). The observed increasing trend in soil compaction over the years can be attributed to the drying trend and decreased organic matter input induced by climate change and poor soil management practices, which result in soil degradation (Akpa et al., 2016; Wasiu et al., 2021; Rodrigues et al., 2023).

Analysis of changes in SOC stock over the years under investigation has been summarized in Table 3.

Table 3: Changes in Soil Organic Carbon Stock (0-30cm depth)

Plant Communities	SOC (2013) Mg ha^{-1}	SOC (2017) Mg ha^{-1}	SOC Change (2013-2017)	SOC (2021) Mg ha^{-1}	Change (2017-2021)
Savanna woodland	44.06	42.94	-1.12	31.77	-11.16
Riparian Forest	39.27	45.85	6.58	31.24	-14.61
Tree Savanna	38.41	32.34	-6.07	29.91	-2.42
Scrubland	35.93	34.47	-1.46	28.48	-5.98
Grassland	35.46	31.14	-4.32	21.92	-9.22
Agroforestry	34.23	34.23	0.00	23.23	-11.00
Old fallow land	30.97	24.58	-6.39	20.32	-4.26
Recent fallow land	29.31	21.07	-8.24	20.92	-0.15
Mean ±Std. Dev.	35.95 ±4.70	33.33±8.31	-2.63	25.97 ±4.85	-7.35

Table 3 indicates that there is a wide range of degraded soils with a depleted SOC stock across the study area. Between 2013-2017, except for the Riparian forest, which had a gain of 6.58 Mg ha^{-1}, all other plant communities experienced a loss in SOC stock, ranging from -1.12 Mg ha^{-1} in the Savanna woodland to -8.24 Mg ha^{-1} in the Recent fallow. However, between 2017 and 2021, virtually all plant communities were at a loss of SOC. The observed decline in SOC could be attributed to unsustainable land management practices that have resulted in soil degradation. The depletion of the SOC stock can be attributed to accelerated erosion, oxidation, mineralization, leaching, acidification, and nutrient depletion (Smith, 2012; Olson, 2013; Odunze et al., 2017; Wasiu et al., 2021; Abdulkadir et al., 2021). Most soils under the managed ecosystems contain a lower SOC pool owing to the unsustainable farming practices, which result in loss of the SOC in cultivated soils (Anikwe, 2010; Obalum et al., 2012; Ndor & Iorkua, 2013; Wasiu, 2021; Nikodemus et al., 2022). The finding of this study is corroborated by Lal (2001), revealing that the most rapid loss of the SOC pool occurs in the first 5 to 10 years of conversion from natural to agricultural ecosystems in the tropics.

3.2 SOC Sequestration Potential

The rate of change and sequestration potential of the various plant communities are presented in Table 4. The mean SOC net change between 2013 and 2021 is -9.98 Mg ha^{-1} for the respective plant communities, while the total net change is -79.84 Mg ha$^{-1,}$ which reflects total carbon emission at an annual rate of 8.87 Mg ha^{-1} yr^{-1}over the years.

Table 4: Rate of Change and Soil Organic Carbon Sequestration Potential

Plant Communities	Net Change SOC Mg ha^{-1} 2013-2021	Annual Rate of Change
Savanna woodland	-12.29	-1.37
Riparian Forest	-8.03	-0.89
Tree Savanna	-8.50	-0.94
Scrubland	-7.44	-0.83
Grassland	-13.54	-1.50
Agroforestry/cropping	-11.00	-1.22
Old fallow land	-10.65	-1.18
Recent fallow land	-8.39	-0.93
Mean	-9.98	-1.11
Total	-79.84	-8.87

The results, as presented in Table 4, have shown that all plant communities have lost some SOC over the years to varying degrees. Therefore, different plant communities and their management systems determine the ability of the soils to sequester carbon (Tegha & Sendze, 2016; Pham et al., 2018). Considering the differences in SOC stock across the sampled plant communities, Grasslands have undergone the highest SOC emission at an annual rate of -1.50 Mg ha^{-1}. Thus, the Grassland has the highest potential to capture more C, especially with the restoration of grasslands to forest plantations (Jiba et al., 2024). This could be explained by the high rate of human interference in the plant communities, manifested by indiscriminate tree logging for farming, housing, and energy (Albaladejo et al., 2013; Ndor & Iorkua, 2013; Akpa et al., 2016; Kadiri et al., 2021). Generally, savanna plant communities are used intensively for food and forage production (Janowiak et al., 2017; FAO & ITPS, 2021), which makes Carbon stocks within the savanna sensitive to management (Poeplau & Don, 2013; Gonçalves et al., 2024) and Savannas are thus vulnerable to losses in soil carbon (Idrissou et al., 2024). Considering the study area as a whole, the sequestration potential is approximately 8.87 Mg ha^{-1} yr^{-1}, if adequate measures are put in place to reverse the trend of soil degradation over the years. The Southern Guinea Savanna has substantial potential to sequester more carbon, especially given that many agricultural soils in the area have been degraded by practices like continuous cultivation and bush burning. The potential to sequester carbon by improving land management practices is substantial, as carbon sequestration would enhance productivity.

Landscapes in the Southern Guinea Savanna ecological zone are critical for sustaining soil fertility, enhancing crop productivity, mitigating climate change, and restoring degraded lands (Onyegbule et al., 2023; Ota et al., 2024). The region has a significant potential for carbon sequestration, particularly through sustainable land management practices (Abegaz et al., 2022), which makes it a potential hotspot for targeted carbon projects. Soil organic carbon (SOC) stock and its sequestration potential are fundamentally relevant to the Sustainable Development Goals (SDGs) as they underpin numerous ecosystem services essential for sustainable development, including food security (SDG 2), climate action (SDG 13), and life on land (SDG 15). Managing and increasing SOC stocks offers a "win-win" strategy that delivers multiple co-benefits across the UN's 2030 Agenda. By implementing sustainable soil management practices, nations can leverage the immense potential of SOC to simultaneously address multiple global challenges and drive progress across the entire sustainable development agenda.

4 Conclusion

This study concludes that the soils of the plant communities in the study area had undergone much carbon loss due to soil degradation processes. The observed carbon loss contributes to total greenhouse gases emission in to the atmosphere. The study also affirms that restoration of the soil carbon stock of various plant communities has the potential to sequester significant carbon from the atmosphere, which will mitigate the impacts of climate change in the southern guinea savanna ecological zone of Nigeria. Losses of soil organic carbon have been identified as a factor that accelerates the greenhouse effect, especially by CO_2 emissions into the atmosphere. Therefore, reversing the trend by the gradual accumulation of SOC over very large areas in savanna landscapes will significantly reduce atmospheric CO_2. Specifically, sequestering carbon in the soil pool by rehabilitating degraded savanna is certainly one way to reduce atmospheric CO_2 and thereby mitigate climate change. This process of soil C sequestration can be sustained by increasing the concentration of SOC through restoration of degraded and drastically disturbed soils by conservation, land-use conversion, and adoption of recommended locally sustainable management practices in agricultural, pastoral, and forestry ecosystems, such as forest protection, fire management, afforestation, species management/selection, use of organic fertilizers, and soil amendments.

Limitations to this study include limited spatial coverage and temporal scale, as the study covers only a fraction of the vast southern guinea savanna ecological zone, and it only covers nine years. Further studies should consider more spatial and temporal scales so as to capture more variability and dynamics that are characteristic of typical environmental variables such as SOC. In terms of soil depth limits, although this study achieved the minimum depth of 0-30cm, it is recommended that further studies should look into lower depths, such as 100cm.

References

Abdulkadir, A., Mohammed, I., & Daudu, C. K. (2021). Organic carbon in tropical soils: Current trends and potential for carbon sequestration in Nigerian cropping systems. In W. Leal Filho et al. (Eds.), Handbook of climate change management (pp. 1–6). Springer. https://doi.org/10.1007/978-3-030-22759-3_307-1

Abdullahi, A. C., Siwar, C., Shaharudin, M. I. I., & Anizan, I. (2018). Carbon sequestration in soils: The opportunities and challenges. IntechOpen. https://doi.org/10.5772/intechopen.79347

Abegaz, A., Ali, A., Tamene, L., Abera, W., & Smith, J. U. (2022). Modeling long-term attainable soil organic carbon sequestration across the highlands of Ethiopia. Environment, Development and Sustainability, 24(5), 5131–5162. https://doi.org/10.1007/s10668-021-01653-0

Abegaz, A., Ali, A., Tamene, L., Abera, W., & Smith, J. U. (2022). Modeling long-term attainable soil organic carbon sequestration across the highlands of Ethiopia. Environment, Development and Sustainability, 24(5), 5131–5162. https://doi.org/10.1007/s10668-021-01653-0

Adekiya, A. O., Alori, E. T., Ogunbode, T. O., Sangoyomi, T., & Oriade, O. A. (2023). Enhancing organic carbon content in tropical soils: Strategies for sustainable agriculture and climate change mitigation. The Open Agriculture Journal, 17(1), 1–15.

Akpa, S. I. C., Odeh, I. O. A., Bishop, T. F. A., Hartemink, A. E., & Amapu, I. Y. (2016). Total soil organic carbon and carbon sequestration potential in Nigeria. Geoderma, 271, 202–215. https://doi.org/10.1016/j.geoderma.2016.02.021

Albaladejo, J., Ortiz, R., Garcia-Franco, N., Navarro, A. R., Almagro, M., Pintado, J. G., & Martínez-Mena, M. (2013). Land use and climate change impact on soil organic carbon stocks in semi-arid Spain. Journal of Soils and Sediments, 13(2), 265–277.

Anikwe, M. A. N. (2010). Carbon storage in soils of southeastern Nigeria under different management practices. Carbon Balance and Management, 5(1), Article 1. https://doi.org/10.1186/1750-0680-5-1

Anokye, J., Logah, V., & Opoku, A. (2021). Soil carbon stock and emission: Estimates from three land-use systems in Ghana. Ecological Processes, 10(1), Article 9. https://doi.org/10.1186/s13717-020-00279-w

Bessah, E., Bala, A., Agodzo, S. K., & Okhimamhe, A. A. (2016). Dynamics of soil organic carbon stocks in the Guinea savanna and transition agro-ecology under different land-use systems in Ghana. Cogent Geoscience, 2(1), Article 1140319. https://doi.org/10.1080/23312041.2016.1140319

Bhardwaj, Y. (2019). Savannah. In J. Vonk & T. Shackelford (Eds.), Encyclopedia of animal cognition and behavior (pp. 1–9). Springer. https://doi.org/10.1007/978-3-319-47829-6_674-1

Castellano, G. R., Santos, L. A., & Menegário, A. A. (2022). Carbon soil storage and technologies to increase soil carbon stocks in the South American savanna. Sustainability, 14(9), Article 5571. https://doi.org/10.3390/su14095571

Ellert, B. H., Janzen, H. H., VandenBygaart, A. J., & Bremer, E. (2008). Measuring change in soil organic carbon storage. In M. R. Carter & E. G. Gregorich (Eds.), Soil sampling and methods of analysis (2nd ed., pp. 25–38). CRC Press.

Food and Agriculture Organization. (2010). Challenges and opportunities for carbon sequestration in grassland systems: A technical report on grassland management and climate change mitigation (Integrated Crop Management Vol. 9). FAO.

Food and Agriculture Organization. (2019). Standard operating procedure for soil organic carbon: Walkley-Black method: Titration and colorimetric method. Global Soil Laboratory Network (GLOSOLAN). https://openknowledge.fao.org/items/efa7ff65-3d95-4b68-ba67-b0aed696b1eb

Food and Agriculture Organization & Intergovernmental Technical Panel on Soils. (2015). Status of the world's soil resources (SWSR) – Main report. FAO.

Food and Agriculture Organization & Intergovernmental Technical Panel on Soils. (2021). Recarbonizing global soils: A technical manual of recommended management practices: Vol. 3. Cropland, grassland, integrated systems and farming approaches – Practices overview. FAO. https://doi.org/10.4060/cb6595en

Forest Management Evaluation and Co-ordinating Unit. (1994). World Bank/Government of Nigeria Forestry III project: Vol. VI. Environmental assessment, forest management component, Kpashimi Forest Reserve [Final draft].

Gonçalves, D. R. P., Inagaki, T. M., Barioni, L. G., La Scala, N., Cherubin, M. R., De Moraes Sá, J. C., Cerri, C. E. P., & Anselmi, A. (2024). Accessing and modelling soil organic carbon stocks in prairies, savannas, and forests. CATENA, 243, Article 108219. https://doi.org/10.1016/j.catena.2024.108219

Grieco, E., Vangi, E., Chiti, T., & Collalti, A. (2024). Impacts of deforestation and land use/land cover change on carbon stock dynamics in Jomoro District, Ghana. Journal of Environmental Management, 367, Article 121993. https://doi.org/10.1016/j.jenvman.2024.121993

Ibrahim, M. M., & Idoga, S. (2013). Soil degradation assessment of the University of Agriculture Makurdi Students Industrial Work Experience Scheme (SIWES) Farm, Makurdi, Benue State. Production Agriculture and Technology, 9(2), 126–135.

Idrissou, Y., Vall, E., Blanfort, V., Blanchard, M., Traoré, I. A., & Lecomte, P. (2024). Integrated crop-livestock effects on soil carbon sequestration in Benin, West Africa. Heliyon, 10(7), Article e28748. https://doi.org/10.1016/j.heliyon.2024.e28748

Intergovernmental Panel on Climate Change. (2003). Good practice guidance for land use, land-use change and forestry. Institute for Global Environmental Strategies.

Intergovernmental Panel on Climate Change. (2014). Summary for policymakers. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx (Eds.), Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Intergovernmental Panel on Climate Change. (2019a). Summary for policymakers. In P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, & J. Malley (Eds.), Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Intergovernmental Panel on Climate Change. (2019b). Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/srccl/

Intergovernmental Panel on Climate Change. (2021). Summary for policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. (In press).

International Institute of Tropical Agriculture. (1992). Medium term plan 1994–1998. IITA.

Jaiyeoba, I. A., & Essoka, P. E. (2006). Soils and vegetation. In The Middle Niger River Basin: A field course handbook (pp. 43–44). Department of Geography, Ahmadu Bello University.

Janowiak, M., Connelly, W. J., Dante-Wood, K., Domke, G. M., Giardina, C., Kayler, Z., Marcinkowski, K., Ontl, T., Rodriguez-Franco, C., Swanston, C., Woodall, C. W., & Buford, M. (2017). Considering forest and grassland carbon in land management (General Technical Report WO-95). U.S. Department of Agriculture, Forest Service.

Jiba, W., Manyevere, A., & Mashamaite, C. V. (2024). The impact of ecological restoration on soil quality in humid region forest habitats: A systematic review. Forests, 15(11), Article 1941. https://doi.org/10.3390/f15111941

Jibrin, A. (2017). Ecological landscape analysis of savanna woodland area in Niger State, Nigeria. Zaria Geographer, 24(1), 119–131.

Jibrin, A., Jaiyeoba, I. A., Iguisi, E. O., & Oladipo, E. O. (2018). Spatial variation of carbon stock density in Guinea savanna landscape of Niger State, Nigeria. Ife Research Publications in Geography, 16(1), 54–64.

Jorge, F., Mutwale-Mutale, N., Sandhage-Hofmann, A., Braun, M., Cambule, A., Nhantumbo, A., Chabala, L. M., Shepande, C., Chishala, B., Lisboa, S., Matangue, M., Schmidt, M., & Amelung, W. (2025). Anthropogenic disturbances superimpose climate effects on soil organic carbon in savanna woodlands of Sub-Saharan Africa. Global Biogeochemical Cycles, 39(2). https://doi.org/10.1029/2023GB008086

Just, C., Armbruster, M., Barkusky, D., Baumecker, M., Diepolder, M., Döring, T. F., et al. (2023). Soil organic carbon sequestration in agricultural long-term field experiments as derived from particulate and mineral-associated organic matter. Geoderma, 434, Article 116472. https://doi.org/10.1016/j.geoderma.2023.116472

Kadiri, W. O. J., Fasina, A. S., & Babalola, T. S. (2021). Soil organic carbon concentration and stock of arable land use of two agro-ecological zones of Nigeria. Journal of the Saudi Society of Agricultural Sciences, 20(3), 180–189. https://doi.org/10.1016/j.jssas.2021.01.004

Kadiri, W., Ogunleye, K., Fasina, A., & Babalola, T. (2023). Soil properties affecting soil organic carbon stock of different land use types in two agro-ecological zones of Nigeria. Agro-Science, 21(3), 37–48. https://doi.org/10.4314/as.v21i3.5

Keay, R. W. J. (1953). An outline of Nigerian vegetation (2nd ed.). Government Printer.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. Science, 304(5677), 1623–1627.

Lal, R. (2015). Soil carbon sequestration and aggregation by cover cropping. Journal of Soil and Water Conservation, 70(6), 329–339. https://doi.org/10.2489/jswc.70.6.329

Lawrence, G. B., Fernandez, I. J., Hazlett, P. W., Bailey, S. W., Ross, D. S., Villars, T. R., Quintana, A., Ouimet, R., McHale, M. R., Johnson, C. E., Briggs, R. D., Colter, R. A., Siemion, J., Bartlett, O. L., Vargas, O., Antidormi, M. R., & Koppers, M. M. (2016). Methods of soil resampling to monitor changes in the chemical concentrations of forest soils. Journal of Visualized Experiments, (117), Article 54815. https://doi.org/10.3791/54815

Mesele, S. A., & Huising, J. (2024). Soil organic carbon and nutrient characteristics of Anogeissus groves in old Opara forest reserve, Nigeria. Environmental Monitoring and Assessment, 196(5), Article 490. https://doi.org/10.1007/s10661-024-12636-9

Ndor, E., & Iorkua, R. S. (2013). Effect of agricultural land use on carbon sequestration and chemical properties of soil in Lafia, Southern Guinea Savanna Agroecological Zone, Nigeria. Global Journal of Biodiversity Science and Management, 3(1), 68–72.

Nigerian Meteorological Agency. (2023). 2022 state of the climate in Nigeria. Federal Ministry of Aviation.

Nikodemus, A., Hájek, M., Ndeinoma, A., & Purwestri, R. C. (2022). Forest ecosystem services-based adaptation actions supported by the national policy on climate change for Namibia: Effectiveness, indicators, and challenges. Forests, 13(11), Article 1965. https://doi.org/10.3390/f13111965

Nwabueze, I. I., Chinero, N. A., & Ngozi, V. O. (2021). Soil carbon dynamics in a humid tropical zone in SE Nigeria: Environmental influences and conservation prioritization. Journal of Geography and Regional Planning, 14(1), 19–31. https://doi.org/10.5897/jgrp2020.0799

Nwaogu, C., Okeke, O. J., Fashae, O., & Nwankwoala, H. (2018). Soil organic carbon and total nitrogen stocks as affected by different land use in an Ultisol in Imo Watershed, southern Nigeria. Chemistry and Ecology, 34(9), 854–870. https://doi.org/10.1080/02757540.2018.1508461

Obalum, S. E., Watanabe, Y., Igwe, C. A., Obi, M. E., & Wakatsuki, T. (2012). Carbon stock in the solum of some coarse-textured soils under secondary forest, grassland fallow, and bare footpath in the derived savanna of south-eastern Nigeria. Soil Research, 50(2), 157–166.

Odebiri, O., Mutanga, O., Odindi, J., Slotow, R., Mafongoya, P., Lottering, R., Naicker, R., Matongera, T. N., & Mngadi, M. (2024). Remote sensing of depth-induced variations in soil organic carbon stocks distribution within different vegetated landscapes. CATENA, 243, Article 108216. https://doi.org/10.1016/j.catena.2024.108216

Odunze, A. C., Yusuf, D. M., & Abdulkadir, A. (2017). Soil organic carbon concentrations and stocks under maize/legume cropping system in Alfisols of a savanna zone, Nigeria. Current Journal of Applied Science and Technology, 1–12. https://doi.org/10.9734/BJAST/2017/32538

Okiemute, E. A. (2025). An appraisal of soil organic carbon content availability under diverse vegetation cover in Delta State, southern Nigeria. Transpublika International Research in Exact Sciences, 4(2), 87–93. https://doi.org/10.55047/tires.v4i2.1687

Olson, K. R. (2013). Soil organic carbon sequestration, storage, retention, and loss in U.S. croplands: Issues paper for protocol development. Geoderma, 195–196, 201–206.

Omotoso, A. B., & Omotayo, A. O. (2024). The interplay between agriculture, greenhouse gases, and climate change in Sub-Saharan Africa. Regional Environmental Change, 24(1), Article 13.

Onyegbule, U. N., Onwudike, S. U., Opara-Nadi, N., & Opara-Nadi, O. (2023). Soil fertility evaluation and land-use effects on soil properties, carbon and nitrogen sequestration in the rainforest of Nigeria. Eurasian Journal of Soil Science, 12(4), 310–319. https://doi.org/10.18393/ejss.1327155

Ota, H. O., Mohan, K., Udume, B. U., Olim, D. M., & Okolo, C. C. (2024). Assessment of land use management and its effect on soil quality and carbon stock in Ebonyi State, Southeast Nigeria. Journal of Environmental Management, 358, Article 120889. https://doi.org/10.1016/j.jenvman.2024.120889

Pham, T. G., Nguyen, H. T., & Kappas, M. (2018). Assessment of soil quality indicators under different agricultural land uses and topographic aspects in Central Vietnam. International Soil and Water Conservation Research, 6(4), 280–288.

Poeplau, C., & Don, A. (2013). Sensitivity of soil organic carbon stocks and fractions to different land-use changes across Europe. Geoderma, 192, 189–201.

Rodrigues, C., Brito, L., & Nunes, L. (2023). Soil carbon sequestration in the context of climate change mitigation: A review. Soil Systems, 7(3), Article 64. https://doi.org/10.3390/soilsystems7030064

Shuaib, M. B., Sauwa, M. M., Musah, M., Onele, E. J., Abdulkareem, Y. J., & Akanbi, E. O. (2025). Quantifying soil carbon stocks and sequestration rate under tree canopy litter in Sudan savannah. Asian Journal of Research in Agriculture and Forestry, 11(3), 36–45. https://doi.org/10.9734/ajraf/2025/v11i3409

Singh, S., Kiran, B. R., & Mohan, S. V. (2024). Carbon farming: A circular framework to augment CO_2 sinks and to combat climate change. Environmental Science: Advances, 3(4), 522–542.

Smith, P. (2012). Soils and climate change. Current Opinion in Environmental Sustainability, 4(5), 539–544.

Tao, H., & Rogers, C. W. (2019). Understanding and measuring organic matter in soil (pp. 1–17). Washington State University

Libraries. https://research.wsulibs.wsu.edu/xmlui/handle/2376/16874

Tegha, K. C., & Sendze, Y. G. (2016). Soil organic carbon stocks in Mount Cameroon National Park under different land uses. Journal of Ecology and the Natural Environment, 8(3), 20–30. https://doi.org/10.5897/JENE2015.0553

Traoré, S., Thiombiano, L., Bationo, B. A., Kögel-Knabner, I., & Wiesmeier, M. (2020). Organic carbon fractional distribution and saturation in tropical soils of West African savannas with contrasting mineral composition. CATENA, 190, Article 104550. https://doi.org/10.1016/j.catena.2020.104550

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science, 37(1), 29–38.

Zhang, P., & Shao, M. (2014). Spatial variability and stocks of soil organic carbon in the Gobi desert of Northwestern China. PLoS ONE, 9(4), Article e93584. https://doi.org/10.1371/journal.pone.0093584

Zhou, Y., Bomfim, B., Bond, W. J., Boutton, T. W., Case, M. F., Coetsee, C., Davies, A. B., February, E. C., Gray, E. F., Silva, L. C. R., Wright, J. L., & Staver, A. C. (2023). Soil carbon in tropical savannas mostly derived from grasses. Nature Geoscience, 16(8), 710–716. https://doi.org/10.1038/s41561-023-01232-0