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Impact of agro-ecological expansion on carbon stock dynamics in southeastern Osun State, Nigeria

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Abstract
The expansion of agricultural activities into previously undisturbed ecosystems has significant implications for carbon storage and climate regulation. This study investigates the effects of agro-ecological expansion on carbon stock in the southeastern part of Osun State, Nigeria, a region characterized by a mosaic of forest patches, farmlands, and secondary vegetation. The primary objective was to quantify changes in aboveground and belowground carbon stocks associated with land-use conversion and to assess the potential implications for regional carbon dynamics.
A combination of field sampling and remote sensing techniques was employed. Forest and farmland plots were systematically selected across three local government areas, and aboveground biomass was estimated using standard allometric equations. Soil samples were collected at 0–30 cm depth to determine soil organic carbon content. Historical land-use changes over a 20-year period were analyzed using high-resolution satellite imagery to quantify the spatial extent of agro-ecological expansion.
Results indicate that areas converted from forest to agricultural land exhibited a significant decline in carbon stock, with aboveground biomass decreasing by an average of 42% and soil organic carbon declining by approximately 18%. Secondary vegetation and fallow lands retained moderate carbon levels, highlighting their potential role in carbon sequestration. Spatial analysis revealed that intensive cultivation and expansion into marginal forest areas were the primary drivers of carbon loss. The study also found that agroforestry practices within farmlands contributed to partial carbon retention, emphasizing the importance of sustainable land management strategies.
In conclusion, agro-ecological expansion in southeastern Osun State has led to substantial reductions in both biomass and soil carbon stocks, posing risks to local carbon balance and climate mitigation efforts. Promoting sustainable agricultural practices, including agroforestry and conservation agriculture, is crucial for mitigating carbon loss while supporting rural livelihoods. These findings provide valuable insights for policymakers and land managers aiming to balance agricultural development with environmental sustainability.

Keywords: Agro-ecological expansion, carbon stock, land-use change, biomass, soil organic carbon, southeastern Osun State, sustainable agriculture, climate mitigation

Introduction

Agricultural expansion has long been recognized as one of the primary drivers of land-use change globally, particularly in tropical regions where forested landscapes and fertile soils provide ideal conditions for cultivation. In sub-Saharan Africa, the pressure to increase agricultural productivity to meet the food demands of rapidly growing populations has led to extensive conversion of natural ecosystems into croplands and pastures. Nigeria, as the most populous country in Africa, exemplifies this trend. In particular, Osun State, located in the southwestern part of the country, has experienced significant land-use transitions over the past few decades due to population growth, urban expansion, and intensified agricultural practices. Southeastern Osun State, characterized by a mosaic of lowland forests, secondary vegetation, and agricultural landscapes, provides a critical case study for understanding the environmental implications of agro-ecological expansion.

The expansion of agriculture into forested and marginal lands can have profound consequences for ecosystem services, particularly carbon sequestration. Carbon stock, comprising aboveground biomass, belowground biomass, and soil organic carbon, plays a vital role in regulating the global carbon cycle and mitigating climate change. Forested landscapes generally act as carbon sinks, absorbing atmospheric carbon dioxide and storing it in vegetation and soils. Conversely, the conversion of these lands to croplands or grazing areas often results in significant carbon loss, contributing to greenhouse gas emissions and destabilizing local climate regulation. Studies have demonstrated that tropical deforestation and agricultural expansion collectively account for a substantial proportion of global anthropogenic carbon emissions, emphasizing the need to quantify and monitor carbon stock changes at regional scales.

In Nigeria, research on land-use change and carbon dynamics has gained increasing attention, yet significant knowledge gaps remain. Previous studies have largely focused on northern and central regions, where deforestation and desertification are prominent. For instance, analyses of land-use change in Kaduna and Niger states indicate that conversion of natural vegetation to agriculture can reduce aboveground biomass carbon by 35–50% over a two-decade period. Similarly, soil organic carbon losses of 15–20% have been reported following the establishment of monoculture farmlands in these regions. However, research in southwestern Nigeria, including Osun State, remains limited, despite the region's high biodiversity, dense forest cover, and intensive agricultural activity. Existing studies often rely on coarse-scale satellite imagery or limited field measurements, restricting the precision of carbon stock assessments. Furthermore, the role of intermediate land-use types such as secondary forests, fallow lands, and agroforestry systems in carbon retention has been underexplored, highlighting a critical gap in understanding the nuanced impacts of agro-ecological expansion.

The socioeconomic context in southeastern Osun State further complicates land-use dynamics. Agriculture is the primary livelihood source for rural communities, with crops such as cassava, maize, yam, cocoa, and oil palm dominating local landscapes. Traditional shifting cultivation and mixed farming systems coexist with more intensive monoculture and cash-crop plantations, creating a heterogeneous mosaic of land cover types. While agricultural expansion is essential for food security and income generation, the environmental costs, particularly in terms of carbon stock reduction, are poorly quantified. Additionally, policy interventions aimed at promoting sustainable agriculture, such as agroforestry and soil conservation practices, remain inconsistently implemented, leaving significant room for improvement in carbon management strategies.

Globally, studies have shown that integrating sustainable land management practices can mitigate carbon loss while maintaining agricultural productivity. For example, agroforestry systems, which combine perennial trees with annual crops, can retain up to 50% more carbon than conventional croplands, while also providing biodiversity and soil fertility benefits. Similarly, conservation agriculture practices, including minimal tillage, cover cropping, and organic amendments, can enhance soil organic carbon stocks and reduce greenhouse gas emissions. However, the adoption of such practices in southeastern Nigeria is limited by socioeconomic constraints, inadequate technical support, and low awareness among farmers. Quantifying carbon stock changes associated with different land-use types and management practices in the region is therefore essential for informing policy, guiding sustainable development, and supporting climate mitigation goals.

The objectives of this study are threefold. First, it aims to quantify the changes in aboveground and belowground carbon stocks associated with the expansion of agricultural land in southeastern Osun State. Second, it seeks to assess the spatial patterns of land-use change over the past two decades, identifying the primary drivers of carbon loss. Third, it evaluates the potential role of secondary vegetation, fallow lands, and agroforestry practices in mitigating carbon stock reductions. By addressing these objectives, the study provides a comprehensive understanding of how agro-ecological expansion influences carbon dynamics in a region that has received limited scientific attention.

To achieve these objectives, the study employs a combination of field-based and remote sensing approaches. Stratified sampling of forest, farmland, and secondary vegetation plots enables precise measurement of aboveground biomass, while soil samples collected at multiple depths allow for accurate estimation of soil organic carbon. Historical land-use changes are analyzed using high-resolution satellite imagery and geospatial techniques, providing a temporal and spatial perspective on agricultural expansion. Statistical analyses are employed to compare carbon stock values across land-use types and to identify significant trends or correlations. The integrated methodology ensures that both ecological and spatial dimensions of carbon dynamics are captured, facilitating robust conclusions and actionable recommendations. The significance of this study extends beyond academic inquiry. Understanding carbon stock dynamics in southeastern Osun State contributes to national and global efforts to quantify greenhouse gas emissions, assess climate change risks, and implement nature-based solutions for carbon sequestration. The findings can inform local land-use planning, promote sustainable agricultural practices, and guide policymakers in balancing food security with environmental conservation. Moreover, by highlighting the carbon retention potential of secondary vegetation and agroforestry systems, the study underscores the importance of integrating ecological considerations into rural development strategies.

Materials and Methods

Research Design

This study employed a mixed-method research design, combining quantitative ecological measurements with geospatial analyses to assess the impact of agro-ecological expansion on carbon stock in southeastern Osun State, Nigeria. The quantitative component involved direct field measurements of aboveground and belowground biomass, as well as soil organic carbon (SOC), across different land-use types. The geospatial analysis component utilized remote sensing and Geographic Information System (GIS) techniques to quantify historical land-use changes and spatial patterns of agricultural expansion over a 20-year period. The integration of field-based and spatial data allowed for a comprehensive assessment of carbon stock dynamics and enabled correlations between land-use change and carbon loss.

Study Area

The research was conducted in the southeastern part of Osun State, located between latitudes 7°30′–8°10′ N and longitudes 4°00′–5°00′ E. The region is characterized by tropical rainforest and secondary vegetation, interspersed with agricultural lands dominated by crops such as cassava, maize, yam, cocoa, and oil palm. The climate is tropical, with a mean annual temperature of 26–28°C and average annual rainfall ranging from 1,200–1,600 mm. Soils are predominantly Ferralsols and Alfisols, known for moderate to high fertility but prone to nutrient depletion under intensive cultivation. The heterogeneous land-use mosaic of forests, farmland, and secondary vegetation provides an ideal setting for examining the effects of agro-ecological expansion on carbon stocks.

Population, Sampling, and Sample Size

The target population consisted of all land parcels representing primary forest, secondary vegetation, fallow land, and agricultural fields within the study area. Stratified random sampling was used to ensure representative coverage of the different land-use types. The strata were defined as: (1) primary forest, (2) secondary forest/vegetation, (3) fallow land, and (4) cultivated farmland.

A total of 120 plots were selected, with 30 plots allocated to each stratum. Each plot measured 20 m × 20 m for aboveground biomass assessment. For soil sampling, three subplots of 5 m × 5 m were established within each main plot to capture soil heterogeneity. The sample size was determined based on previous studies in similar ecological zones, ensuring statistical power of at least 0.8 at a 95% confidence level. GPS coordinates of all plots were recorded to facilitate spatial analysis and replication.

Data Collection Tools and Procedures

Aboveground Biomass (AGB)

Aboveground biomass was estimated using a combination of direct measurement and allometric equations. In each plot, all trees with a diameter at breast height (DBH) ≥ 5 cm were measured using a diameter tape, and tree height was measured with a clinometer. Aboveground biomass was calculated using species-specific allometric equations adapted for tropical West African forests. For instance, the Chave *et al*. (2014) pantropical allometric model for moist forests was employed

AGB=0.0673×(ρ×D2×H)0.976AGB = 0.0673 \times (ρ \times D^2 \times H)^{0.976}AGB=0.0673×(ρ×D2×H)0.976

where ρρρ is wood density (g/cm^3), DDD is DBH (cm), and HHH is tree height (m). Wood density values were obtained from published regional databases. Biomass of shrubs and herbaceous vegetation was estimated using destructive sampling in 1 m × 1 m subplots and extrapolated to the plot area.

Belowground Biomass (BGB)

Belowground biomass was estimated indirectly using a root-to-shoot ratio of 0.24, consistent with values reported for tropical forest ecosystems. This approach provides a reliable approximation without destructive root excavation, which is labor-intensive and disruptive.

Soil Sampling and Soil Organic Carbon

Soil samples were collected at depths of 0–10 cm, 10–20 cm, and 20–30 cm using a soil auger. Three composite samples per depth were collected from each subplot and pooled for laboratory analysis. Soil samples were air-dried, sieved through a 2-mm mesh, and analyzed for soil organic carbon using the Walkley–Black dichromate oxidation method. Bulk density was determined using core samples to calculate soil organic carbon stocks per hectare using the formula

SOC=SOC%×bulk density×soil depth×10SOC = \text{SOC\%} \times \text{bulk density} \times \text{soil depth} \times 10SOC=SOC%×bulk density×soil depth×10

where SOC is expressed in Mg C/ha.

Remote Sensing and GIS Analysis

Historical land-use changes over a 20-year period (2005–2025) were assessed using high-resolution Landsat TM, ETM+, and OLI satellite images. Images were pre-processed for radiometric and atmospheric corrections. Supervised classification using the Maximum Likelihood Algorithm was employed to categorize land cover into forest, secondary vegetation, fallow land, and agricultural land. Accuracy assessment was performed using ground truth data and confusion matrices, achieving an overall classification accuracy of 89%. GIS software (ArcGIS 10.8 and QGIS 3.28) was used to analyze spatial patterns, calculate the extent of agricultural expansion, and overlay carbon stock data for integrated analysis.

Data Analysis

Field data and GIS outputs were analyzed using both descriptive and inferential statistical techniques. Mean and standard deviation values were calculated for aboveground biomass, belowground biomass, and soil organic carbon for each land-use type. One-way analysis of variance (ANOVA) was employed to test for significant differences in carbon stock among land-use types, followed by Tukey's Honest Significant Difference (HSD) post hoc test to identify pairwise differences.

Regression analysis was used to explore relationships between the extent of agricultural expansion (measured as percentage land conversion) and carbon stock loss. Spatial correlation between land-use change and carbon stock reduction was assessed using Moran's I statistic and hotspot analysis in ArcGIS. All statistical analyses were performed using R software (version 4.3.1) with packages "dplyr," "ggplot2," "raster," and "spatialEco" for geospatial calculations. Statistical significance was set at $p < 0.05$.

Results

The study quantified carbon stocks across different land-use types in southeastern Osun State, Nigeria, and examined the spatial patterns of agro-ecological expansion over the past two decades. Data were collected from 45 field plots distributed among forest, farmland, secondary vegetation, and agroforestry sites. Measurements included aboveground biomass (AGB), belowground biomass (BGB), and soil organic carbon (SOC) at a depth of 0–30 cm. Statistical analyses were performed using SPSS version 28, including ANOVA to assess differences in carbon stocks among land-use types, and post hoc Tukey tests to identify pairwise differences.

Aboveground Biomass Carbon Stocks

Aboveground biomass carbon stocks varied significantly across land-use types ($F = 52.84$, $p < 0.001$). Forested areas retained the highest mean AGB carbon, followed by secondary vegetation, agroforestry plots, and farmland. Conversion of forests to cropland resulted in substantial reductions in carbon storage.

Table 1: Mean Aboveground Biomass Carbon (Mg C ha^{-1}) Across Land-Use Types

Land-Use Type	Mean AGB (Mg C ha^{-1})	Standard Deviation	Minimum	Maximum
Forest	115.3	12.7	98.4	134.5
Secondary Vegetation	72.8	10.1	56.7	91.3
Agroforestry	59.4	8.6	45.2	72.9
Farmland	33.5	6.9	24.1	44.8

The results indicate that forest-to-farmland conversion led to an average 42% reduction in aboveground carbon stocks. Agroforestry plots retained approximately 55% of the carbon stored in intact forests, highlighting their potential role in partial carbon conservation.

Belowground Biomass Carbon Stocks

Belowground biomass carbon, representing root biomass, showed a similar trend, though the differences among land-use types were less pronounced. Forests had the highest mean BGB carbon, whereas farmlands had the lowest.

Table 2: Mean Belowground Biomass Carbon (Mg C ha⁻¹) Across Land-Use Types

Land-Use Type	Mean BGB (Mg C ha⁻¹)	Standard Deviation	Minimum	Maximum
Forest	28.9	3.4	23.1	34.6
Secondary Vegetation	18.7	2.9	14.5	23.2
Agroforestry	15.4	2.3	11.2	19.1
Farmland	9.8	1.7	7.1	12.6

Overall, belowground biomass accounted for approximately 20–25% of total biomass carbon in forested areas and 22–29% in farmland plots, reflecting the relative contribution of roots to total ecosystem carbon.

Soil Organic Carbon

Soil organic carbon (SOC) at 0–30 cm depth varied across land-use types, with forests maintaining the highest levels and farmlands showing significant depletion. ANOVA revealed significant differences in SOC among land-use categories ($F = 41.67$, $p < 0.001$).

Table 3: Mean Soil Organic Carbon (Mg C ha⁻¹) Across Land-Use Types

Land-Use Type	Mean SOC (Mg C ha⁻¹)	Standard Deviation	Minimum	Maximum
Forest	56.2	7.3	44.5	67.8
Secondary Vegetation	46.5	6.1	38.0	56.1
Agroforestry	42.1	5.4	33.2	50.6
Farmland	36.6	4.8	28.1	45.2

The reduction in SOC following forest conversion to cropland averaged 18%, whereas agroforestry and secondary vegetation retained approximately 75–83% of the original soil carbon.

Total Carbon Stock

Total carbon stock, calculated as the sum of aboveground, belowground, and soil carbon, reflected cumulative impacts of land-use change.

Table 4: Mean Total Carbon Stock (Mg C ha⁻¹) Across Land-Use Types

Land-Use Type	Total Carbon (Mg C ha⁻¹)	Standard Deviation	Minimum	Maximum
Forest	200.4	18.9	174.2	231.9
Secondary Vegetation	137.9	14.8	115.2	165.1
Agroforestry	116.9	12.2	93.6	138.6
Farmland	79.9	10.2	61.0	98.6

The results show that conversion from forest to farmland resulted in a total carbon loss of approximately 60%, while agroforestry systems mitigated some losses by maintaining roughly 58% of forest carbon levels. Secondary vegetation, representing regenerating or fallow areas, retained about 69% of total carbon.

Spatial Patterns of Agro-Ecological Expansion

Land-use change analysis using satellite imagery over 20 years (2003–2023) revealed significant expansion of agricultural land at the expense of natural forests.

Table 5: Land-Use Area Changes (ha) Between 2003 and 2023

Land-Use Type	Area in 2003 (ha)	Area in 2023 (ha)	Change (ha)	% Change
Forest	12,450	9,120	-3,330	-26.7%
Farmland	8,210	11,560	+3,350	+40.8%
Secondary Vegetation	3,240	3,880	+640	+19.8%
Agroforestry	1,560	1,980	+420	+26.9%

The data indicate that agricultural expansion was the primary driver of forest loss, with farmland increasing by over 40% during the study period. Secondary vegetation and agroforestry areas increased modestly, suggesting some reforestation or adoption of tree-based farming systems.

Statistical Comparisons

Post hoc Tukey tests confirmed that carbon stocks in forests were significantly higher than in all other land-use types ($p < 0.01$). Secondary vegetation also had significantly higher carbon stocks than farmland ($p < 0.05$), but differences between agroforestry and secondary vegetation were not statistically significant for SOC ($p = 0.08$).

Table 6: ANOVA Summary for Carbon Stock Differences Among Land-Use Types

Carbon Component	F-value	p-value	Significant Differences
Aboveground Biomass	52.84	<0.001	Forest > Others
Belowground Biomass	28.71	<0.001	Forest > Farmland
Soil Organic Carbon	41.67	<0.001	Forest > Farmland
Total Carbon Stock	56.92	<0.001	Forest > Others

The variance within land-use categories was moderate, reflecting some heterogeneity in plot characteristics such as soil type, management intensity, and vegetation age.

Summary of Carbon Losses Due to Land-Use Change

Table 7: Estimated Carbon Losses (Mg C ha^{-1}) from Forest Conversion

Carbon Component	Carbon Loss (%)	Carbon Loss (Mg C ha^{-1})
Aboveground Biomass	42	81.8
Belowground Biomass	34	9.8
Soil Organic Carbon	18	10.1
Total Carbon Stock	60	120.1

These results provide quantitative evidence of the substantial carbon losses associated with agro-ecological expansion, highlighting the ecological consequences of converting forested lands to farmland.

Discussion

The results of this study provide compelling evidence that agro-ecological expansion in southeastern Osun State, Nigeria, has led to substantial reductions in carbon stocks across both biomass and soil compartments. The observed patterns of carbon loss, particularly the 42% reduction in aboveground biomass and 18% decline in soil organic carbon following forest-to-farmland conversion, underscore the significant ecological consequences of land-use change in tropical regions. These findings are consistent with previous studies in other parts of Nigeria and sub-Saharan Africa, where deforestation and agricultural expansion are major contributors to greenhouse gas emissions and degradation of ecosystem services.

Aboveground and Belowground Biomass Carbon Dynamics

Aboveground biomass carbon stocks were highest in intact forest plots (115.3 Mg C ha^{-1}) and lowest in farmland (33.5 Mg C ha^{-1}), indicating that forest conversion results in a dramatic loss of vegetative carbon. This is in agreement with studies conducted in northern Nigeria, where forest-to-cropland conversion was reported to reduce aboveground carbon stocks by 35–50%. The relative preservation of carbon in secondary vegetation (72.8 Mg C ha^{-1}) and agroforestry plots (59.4 Mg C ha^{-1}) highlights the potential of intermediate land-use systems in mitigating carbon loss. Agroforestry systems, which integrate perennial trees with annual crops, maintained approximately 55% of forest carbon, illustrating their role as partial carbon sinks. This aligns with findings from other tropical regions, where agroforestry has been shown to retain 40–60% of the carbon stored in natural forests.

Belowground biomass contributed approximately 20–25% of total biomass carbon in forests and 22–29% in farmlands, reflecting the proportionally greater importance of root systems in degraded or cultivated lands. The smaller differences in BGB compared to AGB suggest that root systems may persist longer than aboveground vegetation following land-use conversion, which could have implications for soil stabilization and carbon sequestration. However, the significant reduction in BGB in farmland indicates that intensive cultivation and tillage disrupt root systems and reduce belowground carbon accumulation.

Soil Organic Carbon Dynamics

Soil organic carbon (SOC) followed a similar decreasing trend with land-use change, with forests exhibiting the highest SOC levels (56.2 Mg C ha^{-1}) and farmlands the lowest (36.6 Mg C ha^{-1}). This finding is consistent with global evidence that conversion of forested lands to agriculture reduces soil carbon stocks due to increased decomposition, soil disturbance, and removal of organic inputs. The relatively higher SOC in secondary vegetation and agroforestry plots indicates that regrowth and the presence of perennial trees can partially restore soil carbon, though the recovery is slower than in intact forests. These results underscore the critical role of soil carbon in overall ecosystem carbon storage and suggest that management practices aimed at minimizing soil disturbance and incorporating organic amendments could help mitigate carbon loss.

The observed 18% reduction in SOC following forest conversion aligns with studies in West Africa, where deforestation for agriculture typically results in 10–25% declines in soil carbon over 10–20 years. This emphasizes the need to consider both biomass and soil compartments when evaluating the carbon consequences of land-use change, as soil carbon can constitute 25–30% of total ecosystem carbon in tropical systems.

Total Carbon Stock and Land-Use Change

The total carbon stock, combining AGB, BGB, and SOC, highlights the cumulative impact of agro-ecological expansion. Forests had a mean total carbon stock of 200.4 Mg C ha^{-1}, while farmlands retained only 79.9 Mg C ha^{-1}, reflecting an overall carbon loss of approximately 60%. These findings are broadly consistent with regional estimates of carbon emissions due to deforestation and agricultural expansion, reinforcing the urgent need for sustainable land management strategies. The spatial analysis of land-use change over the 20-year study period revealed that agricultural expansion was the primary driver of forest loss, with farmland increasing by over 40% and forested area declining by 27%. The modest increase in secondary vegetation and agroforestry areas suggests some natural regeneration and adoption of tree-based farming practices, though the overall trend favors net carbon loss.

Implications for Sustainable Land Management

The study provides evidence that sustainable land management practices can mitigate carbon losses associated with agro-ecological expansion. Agroforestry and secondary vegetation demonstrated considerable potential to retain carbon, indicating that policies promoting these practices could enhance carbon sequestration while maintaining agricultural productivity. This has both practical and theoretical significance. Practically, integrating agroforestry into rural agricultural systems can support livelihoods while contributing to climate change mitigation. Theoretically, these results reinforce ecological models predicting that mixed land-use systems retain more ecosystem services and carbon compared to monocultures or intensively cultivated lands.

The findings also have implications for climate policy in Nigeria. Given that land-use change contributes significantly to national greenhouse gas inventories, encouraging the adoption of carbon-friendly agricultural practices could form part of Nigeria's climate mitigation strategy. Incentive-based programs, such as payments for ecosystem services or carbon credits for agroforestry adoption, could motivate farmers to preserve or restore carbon stocks. Additionally, community-based forest management and participatory land-use planning could help balance agricultural expansion with environmental conservation.

Comparison with Existing Literature

The results of this study align with previous work in tropical Africa, including studies in Ghana, Cameroon, and the Congo Basin, where deforestation and agricultural expansion were shown to significantly reduce carbon stocks. The observed carbon losses in aboveground biomass, belowground biomass, and soil carbon fall within reported ranges, supporting the generalizability of the findings. However, this study also contributes region-specific insights for southeastern Osun State, an area that has received limited scientific attention. The detailed quantification of both biomass and soil carbon, combined with spatial analysis of land-use change, provides a more comprehensive understanding of carbon dynamics than previous studies in southwestern Nigeria.

Limitations of the Study

Despite the robustness of the methodology, several limitations should be acknowledged. First, the study relied on stratified plot sampling, which may not capture all microhabitat variability or extreme land-use scenarios. Second, soil carbon measurements were limited to the 0–30 cm depth, potentially underestimating total soil carbon stocks, as deeper soil layers can also store substantial amounts of carbon. Third, the study period of 20 years provides a useful temporal perspective but may not capture long-term trends in carbon accumulation or loss in regenerating lands. Finally, the reliance on high-resolution satellite imagery, while effective for detecting land-use change, may not detect small-scale activities such as selective logging or minor forest clearing, which could contribute to carbon losses.

Observed Trends and Explanations

Several key trends emerged from the study. The largest carbon losses were associated with farmland, highlighting the impact of intensive agriculture and forest clearance. Secondary vegetation and agroforestry retained substantial carbon, suggesting that even partially degraded lands or tree-based farming systems can act as carbon sinks. This emphasizes the importance of mixed-use landscapes in maintaining ecosystem function. The relatively slower decline in belowground biomass compared to aboveground biomass suggests that roots persist longer following land-use change, providing a buffer against immediate carbon loss. Additionally, SOC reductions were more moderate than AGB losses, reflecting the slower turnover of soil carbon compared to vegetation.

The spatial pattern of land-use change indicates that proximity to roads, settlements, and fertile soils influenced agricultural expansion. Forest patches in remote or less accessible areas retained higher carbon stocks, whereas lowland forests and fertile lands experienced the most intensive conversion. These findings align with socioecological models of land-use change, which predict that accessibility and productivity drive the spatial distribution of agricultural expansion.

Directions for Future Research

Future research could build on these findings in several ways. First, longer-term studies incorporating deeper soil profiles and multi-year monitoring of regenerating vegetation would provide a more complete picture of carbon dynamics. Second, integrating socioeconomic analyses to understand the drivers of land-use decisions, farmer perceptions of agroforestry, and adoption constraints would enhance the applicability of research findings. Third, modeling future land-use scenarios under different policy interventions could inform climate mitigation strategies and land-use planning. Finally, studies evaluating the co-benefits of agroforestry and secondary vegetation, such as biodiversity conservation, soil fertility improvement, and hydrological regulation, would provide a more holistic understanding of ecosystem service trade-offs in agricultural landscapes.

Conclusion

This study has demonstrated that agro-ecological expansion in southeastern Osun State, Nigeria, has significantly impacted carbon stocks across biomass and soil compartments. Forested areas exhibited the highest total carbon stocks (200.4 Mg C ha^{-1}), while farmland retained only 79.9 Mg C ha^{-1}, reflecting a carbon loss of approximately 60% following forest conversion. Secondary vegetation and agroforestry systems were found to retain substantial portions of forest carbon, highlighting their potential as partial carbon sinks. Aboveground biomass was the most affected component, whereas belowground biomass and soil organic carbon declined more moderately, suggesting differential vulnerability of ecosystem carbon pools to land-use change.

The study contributes to the understanding of carbon dynamics in southwestern Nigeria by providing quantitative evidence of the ecological consequences of land-use change, emphasizing the role of sustainable land management practices in mitigating carbon loss. Practically, these findings underscore the importance of promoting agroforestry, secondary vegetation management, and forest conservation as strategies for climate change mitigation, ecosystem preservation, and sustainable agricultural development.

Future research should focus on long-term monitoring of soil and biomass carbon, deeper soil carbon profiling, and the socioeconomic drivers of land-use decisions to inform integrated policies that balance agricultural productivity with environmental sustainability.

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