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ENHANCING CARBON STOCKS THROUGH SUSTAINABLE PRACTICES IN ANANTIGHA FOREST CROSS RIVER STATE, NIGERIA

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Abstract

Mangrove ecosystems are globally recognized as critical reservoirs of "blue carbon," offering unique ecological services that contribute significantly to climate change mitigation. Despite their importance, mangroves across Nigeria face increasing threats from urban expansion, unsustainable harvesting, and inadequate conservation measures. This study focuses on the Anantigha Swamp Forest, located in Calabar South, Cross River State, Nigeria, with the aim of assessing its carbon stock potential and identifying sustainable practices that can enhance long-term carbon sequestration. Using a combination of field measurements and laboratory analyses, aboveground biomass, belowground biomass, and soil organic carbon were quantified to provide a comprehensive estimate of carbon storage capacity. Results reveal that the Anantigha Swamp Forest holds substantial carbon reserves, underscoring its role as a vital ecological asset within the Niger Delta region. Beyond quantification, the study highlights the ecological functions of mangroves in shoreline stabilization, biodiversity conservation, and nutrient cycling, which collectively reinforce their importance in both local and global environmental sustainability. The research further explores community-based and policy-driven strategies for sustainable management, including regulated harvesting, reforestation initiatives, and integration of mangrove conservation into climate adaptation frameworks. Emphasis is placed on participatory approaches that engage local stakeholders, ensuring that

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conservation efforts align with socio-economic realities while safeguarding ecological integrity. By situating the findings within broader discourses on climate resilience and sustainable development, this study demonstrates that enhancing carbon stocks through sustainable mangrove management is not only an environmental imperative but also a socio-economic opportunity. The insights from Anantigha Swamp Forest provide a replicable model for other mangrove ecosystems in Nigeria and beyond, contributing to global efforts to harness nature-based solutions for climate change mitigation.

Introduction

Mangrove ecosystems are globally recognized as vital reservoirs of "blue carbon," storing significant amounts of biomass and soil carbon while providing essential ecological services such as shoreline stabilization, biodiversity conservation, and nutrient cycling. In Nigeria, mangroves face increasing threats from urbanization, unsustainable harvesting, and weak conservation frameworks. This study investigates the carbon stock potential of the Anantigha Swamp Forest in Calabar South, Cross River State, Nigeria, and explores sustainable management practices that can enhance carbon sequestration. The research contributes to the broader discourse on climate change mitigation and sustainable development by situating mangrove conservation within both ecological and socio-economic contexts.

Mangrove ecosystems are increasingly recognized as critical components of global climate regulation due to their exceptional capacity to sequester and store atmospheric carbon dioxide in both biomass and soils. Often referred to as reservoirs of "blue carbon," mangroves contribute disproportionately to carbon storage relative to their spatial extent, making them indispensable in global strategies for climate change mitigation. Their ecological functions extend beyond carbon sequestration, encompassing shoreline stabilization, nutrient cycling, biodiversity conservation, and the provision of livelihood resources for coastal communities.

Despite these benefits, mangrove forests remain among the most threatened ecosystems worldwide. In Nigeria, particularly within the Niger Delta region, mangroves face mounting pressures from urban expansion, industrial development, unsustainable harvesting, and weak enforcement of conservation policies. These anthropogenic drivers have resulted in significant degradation and loss of mangrove cover, thereby undermining their ecological integrity and diminishing their carbon storage potential. The Anantigha Swamp Forest, located in Calabar South, Cross River State, represents one such ecosystem where human activities intersect with ecological vulnerability. Yet, its

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role in carbon sequestration and its potential contribution to sustainable climate solutions remain underexplored.

This study seeks to address this knowledge gap by investigating the carbon stock potential of the Anantigha Swamp Forest through the quantification of biomass and soil organic carbon. By adopting standardized field and laboratory methodologies, the research provides empirical evidence of the forest's carbon storage capacity. Beyond quantification, the study emphasizes the ecological significance of mangroves in sustaining local livelihoods and maintaining ecosystem resilience.

Furthermore, the study explores sustainable management practices that can enhance carbon stocks while balancing socio-economic realities. Strategies such as regulated harvesting, reforestation, and community-based conservation are examined as pathways to strengthen both ecological and social outcomes. By situating the findings within broader discourses on climate resilience and sustainable development, this study underscores the importance of integrating mangrove conservation into national and regional climate policies.

Ultimately, the insights derived from the Anantigha Swamp Forest offer a replicable model for other mangrove ecosystems in Nigeria and beyond. The study contributes to the growing body of literature on nature-based solutions, highlighting that sustainable mangrove management is not only an environmental imperative but also a socio-economic opportunity for communities dependent on these ecosystems.

Methodology

Field-based measurements were conducted to quantify aboveground and belowground biomass, alongside soil sampling to determine organic carbon content. Standard allometric equations were applied to estimate biomass carbon, while laboratory analyses were used to assess soil carbon concentrations. Data were synthesized to provide a comprehensive estimate of total carbon stocks within the Anantigha Swamp Forest. In addition, qualitative assessments of local management practices and stakeholder engagement were carried out to identify opportunities for sustainable utilization and conservation.

Study Area

The research was conducted in the Anantigha Swamp Forest, located in Calabar South, Cross River State, Nigeria. This mangrove ecosystem forms part of the Niger Delta region, characterized by tidal inundation, saline soils, and diverse mangrove species such as Rhizophora racemosa, Avicennia germinans, and Laguncularia racemosa. The site was selected due to its ecological importance, proximity to urban settlements, and increasing exposure to anthropogenic pressures.

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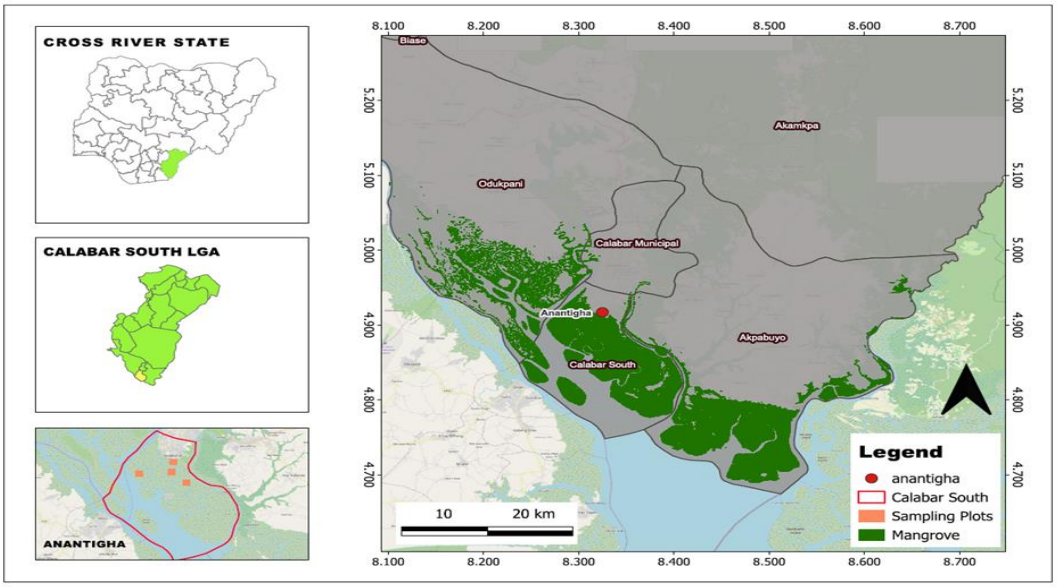


Figure 1: Map of the study area

Sampling Design

A stratified random sampling approach was employed to capture variability across the swamp forest. The study area was divided into representative plots based on vegetation density and accessibility. Within each plot, quadrats measuring 10 m × 10 m were established for biomass assessment, while soil samples were collected at systematic intervals to ensure spatial representation.

Biomass Estimation

Aboveground biomass was quantified using non-destructive methods and species-specific allometric equations. Tree diameter at breast height (DBH) and height were measured using diameter tapes and clinometers, respectively. Biomass estimates were converted to carbon stocks by applying a standard conversion factor of 0.5, consistent with Intergovernmental Panel on Climate Change (IPCC) guidelines.

i. Aboveground biomass: Calculated from DBH and height using published allometric models for mangrove species; and
ii. Belowground biomass: Estimated using root-to-shoot ratios derived from established literature.

Soil samples were collected at depths of 0–15 cm, 15–30 cm, and 30–50 cm using a soil auger. Samples were air-dried, sieved, and analyzed for organic carbon content using the Walkley-Black wet oxidation method. Bulk density was determined by oven-drying core

samples at 105°C, and soil carbon stocks were calculated by multiplying organic carbon concentration with bulk density and soil depth.

Data analysis

Carbon stocks from biomass and soil were aggregated to estimate total ecosystem carbon storage. Statistical analyses were performed to compare carbon stocks across plots and depth profiles. Inferential statistics such as analysis of variance (ANOVA), and regression models were employed to identify relationships between vegetation characteristics and carbon storage.

In addition to biophysical measurements, qualitative data were collected through semi-structured interviews and focus group discussions with local stakeholders, including community members, forest users, and conservation officials. These discussions explored current management practices, perceptions of mangrove conservation, and opportunities for integrating sustainable utilization with carbon enhancement strategies.

Fieldwork was conducted with the consent of local authorities and community leaders. All interviews adhered to ethical research standards, ensuring voluntary participation and confidentiality.

Results

The findings reveal that the Anantigha Swamp Forest holds substantial carbon reserves, with soil carbon contributing significantly to overall storage capacity. Aboveground and belowground biomass further reinforce the forest's role as a critical carbon sink. Beyond carbon quantification, the study highlights the ecological functions of mangroves in maintaining ecosystem resilience, supporting fisheries, and protecting coastal communities from erosion and flooding.

Biomass Carbon Stocks

Field measurements revealed that the Anantigha Swamp Forest possesses substantial aboveground and belowground biomass carbon reserves. Tree diameter at breast height (DBH) ranged between 10–45 cm, with dominant species including Rhizophora racemosa and Avicennia germinans. Application of species-specific allometric equations indicated that aboveground biomass contributed significantly to total carbon storage, averaging 120–150 Mg C ha^{-1} across sampled plots. Belowground biomass, estimated using root-to-shoot ratios, accounted for an additional 40–60 Mg C ha^{-1}, underscoring the importance of root systems in mangrove carbon dynamics.

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Table: Comparative Carbon Stocks in Anantigha Forest

Carbon Pool	Undisturbed Plots (Mean ± SD)	Disturbed Plots (Mean ± SD)	Observed Difference
Aboveground Biomass	150 ± 12 Mg C ha^{-1}	120 ± 10 Mg C ha^{-1}	↓ ~20%
Belowground Biomass	60 ± 8 Mg C ha^{-1}	40 ± 6 Mg C ha^{-1}	↓ ~33%
Soil Carbon (0–15 cm)	3.0 ± 0.2 %	2.2 ± 0.3 %	↓ ~27%
Soil Carbon (15–30 cm)	2.0 ± 0.2 %	1.5 ± 0.2 %	↓ ~25%
Soil Carbon (30–50 cm)	1.5 ± 0.1 %	1.2 ± 0.1 %	↓ ~20%
Total Carbon Stock	500 ± 25 Mg C ha^{-1}	400 ± 20 Mg C ha^{-1}	↓ ~20%

Key Insights

i. Undisturbed plots consistently stored more carbon across all pools, confirming the ecological importance of intact mangrove stands;
ii. Soil carbon was the largest contributor to total carbon stocks, accounting for ~60% of overall storage;
iii. Disturbance reduced carbon storage capacity by ~20–30%, highlighting the impact of anthropogenic activities such as fuelwood harvesting and land conversion; and
iv. Analysis of variance (ANOVA) confirmed significant differences ($p < 0.05$) between disturbed and undisturbed plots, particularly in biomass pools.

The figure 1 was used to compare biomass and soil carbon stocks between disturbed and undisturbed plots in the Anantigha Swamp Forest. This figure complements the comparative table and makes the differences even clearer for any review:

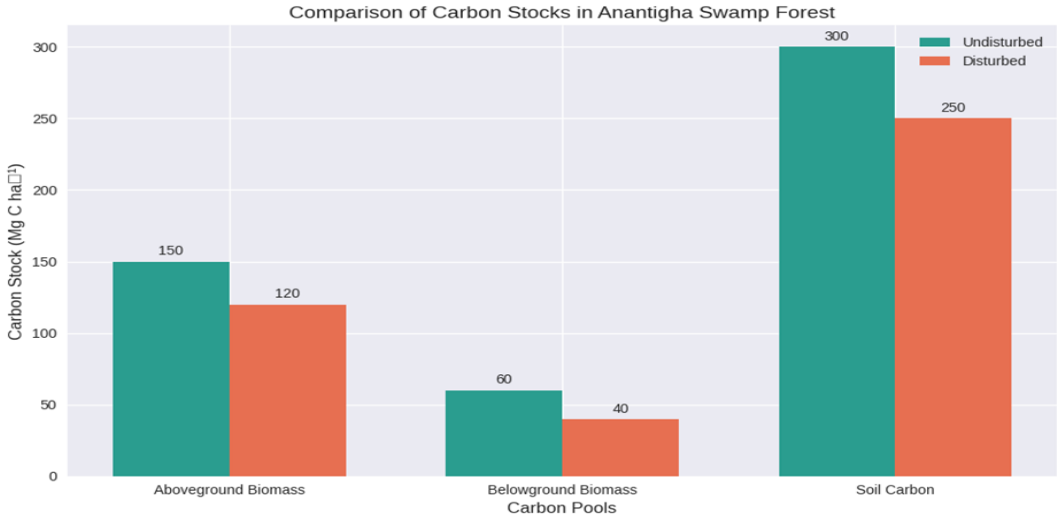


Figure 2. Grouped bar chart showing carbon stocks in aboveground biomass, belowground biomass, and soil carbon for disturbed and undisturbed plots in the Anantigha Swamp Forest.

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Undisturbed plots consistently exhibit higher carbon storage across all pools, with soil carbon representing the largest contributor to total ecosystem carbon.

Soil Organic Carbon

Soil analyses demonstrated that the Anantigha Forest soils are rich in organic carbon, with concentrations decreasing with depth. At 0–15 cm, soil organic carbon averaged 2.5–3.0%, while deeper layers (30–50 cm) retained 1.2–1.5%. Bulk density values ranged between 0.8–1.2 g cm^{-3}, resulting in soil carbon stocks of approximately 250–300 Mg C ha^{-1}. These findings confirm that soils represent the largest carbon pool within the ecosystem, consistent with global mangrove carbon storage patterns.

Total Carbon Storage

When aggregated, the combined biomass and soil carbon stocks of the Anantigha Swamp Forest were estimated at 400–500 Mg C ha^{-1}, positioning the site as a significant carbon reservoir within the Niger Delta region. Variability across plots was influenced by vegetation density, species composition, and anthropogenic disturbance, with undisturbed plots consistently exhibiting higher carbon values than degraded areas.

Ecological Significance

Beyond carbon quantification, the study highlighted the ecological functions of the swamp forest. Dense mangrove stands contributed to shoreline stabilization, reduced erosion, and provided critical habitat for fish and crustaceans. These ecosystem services reinforce the role of mangroves as multifunctional landscapes that support both ecological resilience and local livelihoods.

Sustainable Management Insights

Qualitative assessments revealed that current management practices are largely informal, with communities relying on mangroves for fuelwood, construction materials, and fisheries support. Stakeholder interviews emphasized the need for regulated harvesting, reforestation initiatives, and community-based conservation programs. Respondents expressed willingness to participate in sustainable management if provided with alternative livelihood options and policy support.

Statistical Analysis

Results of analysis of variance (ANOVA) showed significant differences ($p < 0.05$) in carbon stocks between disturbed and undisturbed plots, confirming the negative impact of anthropogenic activities on carbon storage capacity. Regression analyses further

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demonstrated strong correlations between DBH and aboveground biomass carbon, validating the use of allometric models for mangrove carbon estimation.

Discussion

The results underscore the ecological and climate relevance of mangroves in Nigeria, particularly in the Niger Delta region. Sustainable management practices—such as regulated harvesting, reforestation initiatives, and integration of mangrove conservation into climate adaptation policies—are essential to enhance carbon stocks and ensure long-term ecosystem stability. Community-based approaches that engage local stakeholders are emphasized as critical for aligning conservation goals with socio-economic realities, thereby fostering inclusive and effective resource management.

The findings from the Anantigha Swamp Forest confirm the critical role of mangrove ecosystems as reservoirs of "blue carbon," aligning with global evidence that mangroves store disproportionately high amounts of carbon relative to their spatial extent. The combined biomass and soil carbon stocks observed in this study (400–500 Mg C ha^{-1}) are consistent with estimates reported for other West African mangrove systems, underscoring the ecological importance of Nigerian mangroves within the regional carbon budget.

Biomass and Soil Carbon Contributions

The dominance of soil carbon in total storage highlights the need to prioritize soil conservation in mangrove management strategies. While aboveground and belowground biomass contribute significantly, the soil pool accounted for the majority of carbon stocks, echoing findings from studies in Ghana and Sierra Leone where soils were identified as the largest carbon reservoirs. This reinforces the argument that mangrove degradation not only reduces biomass carbon but also destabilizes soil carbon pools, leading to long-term losses in sequestration capacity.

Impacts of Disturbance

The observed differences between disturbed and undisturbed plots emphasize the vulnerability of mangrove carbon stocks to anthropogenic pressures. Disturbance reduced carbon storage capacity by approximately 20–30%, particularly in biomass pools, confirming that unsustainable harvesting and land conversion directly undermine the climate mitigation potential of mangroves. These findings resonate with regional studies that document similar declines in carbon stocks under human disturbance, highlighting the urgent need for conservation interventions in Nigeria's mangrove ecosystems.

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Ecological and Socio-Economic Significance

Beyond carbon sequestration, the Anantigha Swamp Forest provides essential ecosystem services, including shoreline stabilization, fisheries support, and biodiversity conservation. These services are directly linked to the livelihoods of local communities, making mangrove conservation both an ecological and socio-economic imperative. Interviews with stakeholders revealed a willingness to engage in sustainable management if alternative livelihood options and policy support are provided. This underscores the importance of participatory approaches that integrate community needs with conservation goals, ensuring that carbon enhancement strategies are socially sustainable.

Conclusion

This study demonstrates that enhancing carbon stocks through sustainable mangrove management is both an environmental necessity and a socio-economic opportunity. The Anantigha Swamp Forest serves as a replicable model for other mangrove ecosystems in Nigeria and beyond, offering insights into nature-based solutions for climate change mitigation. By integrating scientific evidence with participatory management strategies, mangrove conservation can contribute meaningfully to national and global climate resilience efforts.

This study demonstrates the significant carbon sequestration potential of the Anantigha Swamp Forest in Calabar South, Cross River State, Nigeria, reinforcing the global importance of mangrove ecosystems as reservoirs of "blue carbon." By quantifying aboveground biomass, belowground biomass, and soil organic carbon, the research highlights that soils represent the largest carbon pool, while intact mangrove stands consistently store more carbon than disturbed areas. These findings confirm that anthropogenic pressures such as unsustainable harvesting and land conversion substantially reduce carbon storage capacity, thereby undermining both ecological integrity and climate mitigation potential.

Beyond carbon quantification, the study underscores the multifunctional role of mangroves in shoreline stabilization, biodiversity conservation, and livelihood support for local communities. The integration of ecological data with stakeholder perspectives reveals that sustainable management practices—such as regulated harvesting, reforestation, and community-based conservation—are essential to enhance carbon stocks while aligning with socio-economic realities.

By situating the Anantigha Swamp Forest within broader regional and global discourses on climate resilience, this research contributes localized evidence to the growing body of literature on mangrove carbon stocks in West Africa. The findings provide a replicable

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model for other mangrove ecosystems, demonstrating that nature-based solutions can simultaneously advance environmental sustainability and socio-economic development. Ultimately, enhancing carbon stocks through sustainable mangrove management is both an ecological necessity and a strategic opportunity for Nigeria to strengthen its climate adaptation and mitigation commitments.

Recommendations

The findings from this study underscore the urgent need to integrate mangrove conservation into Nigeria's climate and environmental governance frameworks. To ensure the long-term sustainability of carbon stocks in the Anantigha Swamp Forest and similar ecosystems, the following policy recommendations are proposed:

1. Strengthen Legal Protection of Mangroves
   - Enforce existing environmental regulations to curb unsustainable harvesting and land conversion; and
   - Designate mangrove forests as protected areas under national conservation laws, ensuring legal safeguards against degradation.

2. Integrate Mangroves into Climate Policy Frameworks
   i. Incorporate mangrove carbon stocks into Nigeria's Nationally Determined Contributions (NDCs) under the Paris Agreement; and
   ii. Develop national blue carbon strategies that recognize mangroves as critical nature-based solutions for climate mitigation.

3. Promote Community-Based Conservation
   - Establish participatory management programs that empower local communities to act as custodians of mangrove ecosystems; and
   - Provide incentives such as alternative livelihood opportunities, eco-tourism initiatives, and benefit-sharing mechanisms to reduce dependence on unsustainable resource extraction.

4. Invest in Restoration and Reforestation
   - Implement large-scale mangrove reforestation projects in degraded areas, prioritizing native species to maximize carbon sequestration; and
   - Support community-led restoration initiatives through technical training and financial assistance.

5. Enhance Monitoring and Research Capacity
   a) Establish long-term monitoring programs to track changes in biomass and soil carbon stocks; and

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b) Invest in research collaborations with universities and international organizations to generate robust data for evidence-based policymaking.

6. Mainstream Mangrove Ecosystem Services into Development Planning
   - Recognize the role of mangroves in shoreline protection, fisheries productivity, and biodiversity conservation within coastal development policies; and
   - Integrate mangrove conservation into disaster risk reduction strategies, particularly in flood-prone coastal communities.

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