International Journal of Engineering Research and Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 21, Issue 12 (December 2025), PP 33-44

Above- and Below-Ground Carbon Stocks of Protected and Disturbed Mangrove Forests in Finima, Bonny Island, Nigeria

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Abstract
Mangrove forests are among the most productive and carbon-rich ecosystems on Earth, providing essential services such as shoreline protection, nursery habitats for fisheries, nutrient cycling, and long-term carbon sequestration. However, degradation from deforestation, wood harvesting, and land conversion releases significant greenhouse gases. Assessing above-ground and below-ground biomass along disturbance gradients is therefore crucial for understanding how human activities affect the climate-mitigation capacity of mangroves, particularly in Nigeria's Niger Delta. This study quantified above-ground biomass (AGB), below-ground biomass (BGB), and soil organic carbon (SOC) across three mangrove sites in Finima, Bonny Island: Finima Nature Park (protected), Pioneers Camp (moderately disturbed), and Lighthouse (highly disturbed). Using standard allometric equations, soil analyses, and geospatial assessments, carbon pools were estimated. Finima recorded the highest total carbon stock (175 Mg C ha⁻¹), followed by Pioneers Camp (145 Mg C ha⁻¹) and Lighthouse (130 Mg C ha⁻¹). SOC and moisture content also declined progressively with increasing disturbance, ranging from SOC = 4.7% and moisture = 72% in Finima to SOC = 2.7% and moisture = 63% in Lighthouse. The disturbance index exhibited strong negative correlations with all carbon-related variables, with coefficients of r = −0.981, −0.972, −0.987, −0.982, and −0.989 for soil carbon, moisture, AGB, BGB, and total carbon, respectively (p < 0.05). These relationships indicate that disturbance consistently reduces carbon-storage components. The findings highlight the urgent need for mangrove conservation and restoration to sustain ecological and socioeconomic functions, including shoreline stabilization, fisheries support, biodiversity maintenance, and climate regulation. Strengthening protection frameworks and promoting community-based restoration are recommended to safeguard mangrove carbon sinks in Bonny Island and across Nigeria's coastal zone.

Keywords: *Above-ground biomass (AGB), Below-ground biomass (BGB), Soil organic carbon (SOC), Mangrove forests*

Date of Submission: 01-12-2025 Date of acceptance: 10-12-2025

I. Introduction

Climate change stands out as one of the most urgent environmental issues of the 21st century, largely fuelled by greenhouse gas particularly CO_2 which concentration is increasing disproportionately to safe levels in the atmosphere resulting from human activities (anthropogenic activities) (Intergovernmental Panel on Climate Change [IPCC], 2021; Nwankwo et al., 2023). According to Nwankwo et al. (2023), carbon dioxide is estimated to contribute approximately three-quarters of the total greenhouse effect. The harmful effects of climate change are expected to last for many decades if intentional steps are not taken to slow the gas's rapid buildup in the atmosphere (Nwankwo et al., 2023). Natural ecosystems and human societies are significantly impacted by both climate change and global warming (Nwankwo et al., 2023). Acute water scarcity, deteriorating water quality, sea level rise and saltwater intrusion due to glacier and ice sheet melting, an increase in storm surges, unpredictable rainfall patterns, and other extreme weather events are some of these effects (Jimenez Cisneros et al., 2014; Ibe, 2017; Nwankwo et al., 2023). Degradation of wetlands, loss of natural resources, changes in plant species distribution, changes in growing seasons, decreased agricultural productivity, increased sediment loads, and accelerated erosion processes are other examples of these changes (IPCC, 2007; Peters et al., 2013 Nwankwo et al., 2023). Adaptive techniques and interventions that lower greenhouse gas emissions and improve the natural processes of carbon sequestration are necessary to address these issues (Nwankwo et al., 2023). As carbon sinks, forest ecosystems are essential to the fight against climate change (Pan et al., 2011). Mangrove forests are particularly significant among them because of their remarkable ability to store carbon, their role in protecting coastal communities from increasing sea levels, and their contribution to biodiversity (Donato et al., 2011; Alongi, 2014).

Located in tropical and subtropical areas, mangrove forests are excellent in removing carbon dioxide (CO_2) from the atmosphere (Giri et al., 2011). These ecosystems are among the best natural measures to combat climate change because they store large amounts of carbon in their biomass and soil (Mcleod et al., 2011; Hamilton & Friess, 2018). But pollution, urbanization, and deforestation pose major risks to mangrove forests, notwithstanding their biological importance (Polidoro et al., 2010; Friess et al., 2019).

Nigeria's growing energy demand remains largely dependent on fossil fuels such as coal, oil, and natural gas. Even if these resources still fuel economic expansion and industrial development, they also contribute significantly to greenhouse gas emissions—more than 60% of global emissions come from them (Ogundipe et al., 2018). Large amounts of carbon dioxide are released into the atmosphere when fossil fuels are used, which exacerbates global warming and has serious negative effects on the ecosystem, including flooding, sea level rise, melting ice caps, and erratic rainfall patterns (Adekomaya et al., 2016; Anomohanran, 2017). These changes have profound effects on food security, water availability, and public health, particularly in developing countries where adaptive capacities are low (Alimi et al., 2016).

In the Niger Delta region, oil exploration and industrial activities have worsened environmental degradation. Extensive mangrove habitats, which are essential carbon sinks that naturally absorb and store atmospheric carbon, have been damaged by frequent oil spills, deforestation, and land conversion (Rhy, 2011). The carbon deposited in mangroves' biomass and soils is released back into the atmosphere when they are destroyed or damaged, which exacerbates global warming. Additionally, biodiversity, fishing production, and coastal protection are all threatened by the loss of these ecosystems. Thus, the purpose of this study is to evaluate the mangrove trees' capacity to sequester carbon both above and below ground in Finima. The findings are expected to provide scientific evidence that can support national climate change mitigation strategies and inform sustainable management of Nigeria's coastal ecosystems

II. Material And Methods

Finima Nature Park (FNP) is located on Bonny Island, Rivers State, Nigeria (Figure 1). It is about 1,000 hectares in area and serves as a major area for mangrove, freshwater swamp, and related ecosystem conservation. FNP, under the Nigerian Conservation Foundation (NCF) management, serves as a focal point for the conservation of biodiversity, carbon sequestration, and coastlines protection. FNP has a humid tropical climate with high rainfall and warm temperature all year round. The park hosts a variety of plant and animal species, including mangrove species such as Rhizophora racemosa, Avicennia germinans, and Laguncularia racemosa that are capable of sequestering carbon.

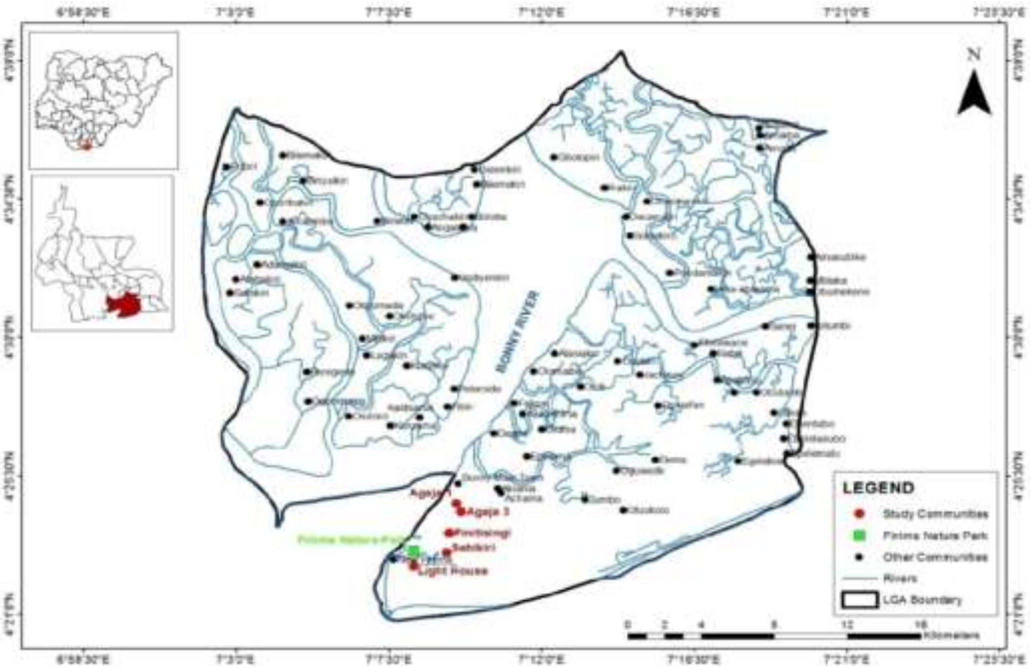

Figure 1: Map of the Study Area (Ijeomah & Duke, 2016)

The study employed a combination of analytical approaches to assess the carbon sequestration potential of mangrove forests in Finima Nature Park. Carbon sequestration analysis involved estimating the biomass of mangrove trees using allometric equations, while carbon content was calculated using established conversion factors. Soil carbon content was determined through laboratory-based analyses. Statistical analysis was carried out with SPSS and R, employing both descriptive and inferential techniques, including regression analysis, to explore correlations between climate variables and mangrove cover. The statistical analysis was designed to evaluate the relationships between anthropogenic disturbance and the carbon storage capacity of mangrove ecosystems across the three study sites, Finima Nature Park (FNP), Pioneers Camp, and Lighthouse located in Bonny Island, Rivers State, Nigeria. Data derived from field measurements (e.g., biomass, soil carbon, and moisture content) and computed indices were subjected to both descriptive and inferential statistical analyses using IBM SPSS version 27 and R (version 4.3.1). The statistical workflow involved three main stages: (i) computation of descriptive statistics, (ii) correlation analysis, and (iii) linear regression modelling. Descriptive statistics were employed to summarize site-level parameters, including the mean, standard deviation, and range for variables such as Disturbance Index (DI), Soil Organic Carbon (SOC), Moisture Content, Above-Ground Biomass (AGB), Below-Ground Biomass (BGB), and Total Carbon Stock (TCS).

Step 1: Identify t threat classes and group these into j categories to get C_t^j, where C_t^j are the threats in each c These statistics provided a baseline understanding of the spatial variability in mangrove structure and carbon storage across the disturbance gradient from protected (Finima) to degraded (Lighthouse) sites. The Disturbance Index was calculated using field measurements of logging intensity, soil compaction, and frequency of human access to create a composite score that ranged from 1 (low disturbance) to 3 (high disturbance). In the analyses that followed, this index was used as the independent variable. To quantify the degree and direction of association among the measured biophysical and disturbance variables, the Pearson Product-Moment Correlation Coefficient (r) was computed. This test was appropriate because the variables were continuous and approximately normally distributed.

The Pearson correlation coefficient is defined mathematically as:

$$r = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2\sum(y_i-\bar{y})^2}} \quad (1)$$

where:

- r= correlation coefficient,
- x_i and y_i= paired observations of variables X(e.g., Disturbance Index) and Y(e.g., Total Carbon Stock),
- $\bar{x}$and $\bar{y}$= mean values of Xand Y, respectively.

The value of rranges between -1 and +1, where:

- $r > 0$indicates a positive (direct) relationship,
- $r < 0$indicates a negative (inverse) relationship, and
- $r = 0$indicates no linear relationship between the variables

Statistical significance was evaluated at $p < 0.05$ (two-tailed test).

This correlation test was performed to determine how increasing levels of anthropogenic disturbance affected biomass (AGB, BGB) and total carbon storage (TCS), as well as how soil carbon and moisture interacted across the mangrove sites.

To further examine the quantitative influence of disturbance index on mangrove carbon storage, a simple linear regression model was developed, where Disturbance Index (DI) served as the independent variable (X) and Total Carbon Stock (TCS) as the dependent variable (Y).

This approach helped establish the predictive relationship and assess the sensitivity of carbon storage to increasing disturbance.

The regression model is represented as:

$$Y = \beta_0 + \beta_1 X + \varepsilon \quad (2)$$

where:

- Y= Total Carbon Stock (Mg C ha^{-1}),
- X= Disturbance Index (unitless),
- β_0= intercept (expected value of Y when X = 0),
- β_1= regression coefficient (rate of change in Y per unit increase in X),
- ε= random error term.

The coefficient of determination (R^2) was used to assess the explanatory power of the model:

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \quad (3)$$

where:

- SS_{res}= residual sum of squares,
- SS_{tot}= total sum of squares.

A high R^2value (close to 1) indicates a strong model fit and that most of the variation in the dependent variable is explained by the independent variable.

III. Results

3.1 Quantification of Above-Ground and Below-Ground Biomass (AGB and BGB)

This study evaluated three distinct mangrove locations to investigate biomass dynamics at varying disturbance intensities. Pioneers Camp and Lighthouse were marked by differing degrees of anthropogenic activity, such as tree felling, timber harvesting, and other human disturbances, whereas Finima Nature Park (FNP) was the control location, representing a protected site under rigorous protection and management. The measured AGB and BGB values across the sites showed a clear disturbance gradient: FNP (AGB = 80 Mg ha^{-1}; BGB = 95 Mg ha^{-1}) > Pioneers Camp (AGB = 65 Mg ha^{-1}; BGB = 80 Mg ha^{-1}) > Lighthouse (AGB = 58 Mg ha^{-1}; BGB = 72 Mg ha^{-1}) (Table 1).

3.2 Total Carbon Stock and Sequestration Capacity

Mangrove forests are globally recognized for their high potential to store and sequester atmospheric carbon. This study assessed both vegetation and soil carbon stocks across three sites; Finima Nature Park (FNP), Pioneers Camp, and Lighthouseto estimate the total carbon storage capacity of mangrove ecosystems in Bonny Island.

The total carbon stock was calculated using the IPCC (2006) default carbon fraction (CF = 0.47). Above-ground and below-ground biomass values were partitioned into their respective components according to FAO guidelines (Food and Agriculture Organization [FAO], 2010) to determine the contributions of trees, branches, leaves, and root fractions to total carbon storage (Santoro et al., 2021). The total carbon stock values indicate that FNP has the greatest carbon storage potential (175 t/ha), followed by Pioneers Camp (145 t/ha) and Lighthouse (130 t/ha), reflecting a direct influence of conservation status and disturbance level (Table 1).

To obtain a more detailed estimate, the above- and below-ground biomass values were disaggregated to calculate the carbon stock of individual components using the conversion factor (×0.47) (Tables 2 – 4). The findings indicate that FNP possesses the highest carbon storage in both above- and below-ground components, reflecting the stability of a protected mangrove ecosystem. The total annual sequestration rate for FNP was estimated at 43 tCO_2/ha/year, consistent with global estimates showing that mangroves can store up to five times more carbon per hectare than terrestrial forests (Donato et al., 2011).

Table 1: Carbon stock distribution across the three study sites.

Carbon Pool	Carbon Stock (t/ha)	FNP	PC	LH
Above-Ground Biomass (Tree biomass, leaves, branches)		80	65	58
Below-Ground Biomass (Root system, sediment organic matter)		95	80	72
Total Carbon Stock		**175**	**145**	**130**

Table 2: Above-Ground Carbon (AGC) Breakdown (tC/ha)

Site	AGB (t/ha)	Tree (×0.47)	Branches (×0.47)	Leaves (×0.47)	AGC Total
FNP	80	26.32	7.52	3.76	37.60
PC	65	21.39	6.11	3.06	30.55
LH	58	19.08	5.45	2.73	27.26

Table 3: Below-Ground Carbon (BGC) Breakdown (tC/ha)

Site	BGB (t/ha)	Coarse roots (×0.47)	Fine roots (×0.47)	Very fine roots (×0.47)	BGC total
FNP	45	14.81	4.23	2.12	21.15
PC	80	26.32	7.52	3.76	37.60
LH	72	23.69	6.77	3.38	33.84

Table 4: Total Ecosystem Carbon stock (AGC + BGC) across study sites

Site	AGC	BGC	Total Carbon (tC/ha)
FNP	37.60	21.15	58.75
PC	30.55	37.60	68.15
LH	27.26	33.84	61.10

3.3 Anthropogenic Influences on Carbon Storage Variation

Field observations across the three study sites in Finima Nature Park (FNP), Pioneers Camp, and Lighthouse, revealed varying degrees of human-induced disturbance, which directly influenced the biomass and carbon storage capacities of the mangrove ecosystems. The types and intensity of anthropogenic activities observed include (Table 5):

- **Tree felling and fuelwood harvesting**, particularly in Pioneers Camp and Lighthouse;

- **Soil compaction and root exposure** resulting from human trampling and extraction activities;
- **Hydrological alterations**, such as blocked tidal channels and land reclamation for settlement and aquaculture;
- **Settlement encroachment** and small-scale exploitation of mangrove products.

These activities were minimal or absent in FNP, which is under formal protection, but they were moderate in Pioneers Camp and severe in Lighthouse. The effects of these disturbances were reflected in the observed decline in above-ground biomass (AGB), below-ground biomass (BGB), and soil organic carbon (SOC) across the gradient from the protected to the disturbed sites.

Table 5: Summary of anthropogenic disturbance and its effect on biomass and carbon storage.

Site	Disturbance Level	Dominant Anthropogenic Activities	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	SOC (%)	Carbon Stock (Mg C ha^{-1})
FNP	Protected (None)	Strictly conserved, no logging	80	95	4.7	175
Pioneers Camp	Moderate	Selective cutting, fuelwood collection	65	80	3.2	145
Lighthouse	High	Uncontrolled tree cutting, land clearing	58	72	2.7	130

The Table 5 illustrates the inverse relationship between disturbance level (index) and carbon storage capacity: as anthropogenic activities increase, both biomass and soil carbon stocks decline. FNP maintained the highest carbon stock (175 Mg ha^{-1}), while Lighthouse recorded the lowest (130 Mg ha^{-1}), showing that unmanaged human interference directly compromises carbon sequestration potential

Figure 2 presents a comparative summary of above-ground biomass (AGB), below-ground biomass (BGB), and total carbon stock for the three study sites. Finima Nature Park recorded the highest AGB (80 Mg ha^{-1}) and BGB (95 Mg ha^{-1}), with a total carbon stock of approximately 175 Mg C ha^{-1}. This reflects the effect of restricted access and effective protection policies within the park.

At Pioneers Camp, moderate disturbance mainly through fuelwood collection and selective cutting resulted in a noticeable decline in biomass, with AGB and BGB values of 65 Mg ha^{-1} and 80 Mg ha^{-1}, respectively. The corresponding carbon stock (145 Mg C ha^{-1}) was lower than at Finima, indicating the impact of partial vegetation removal on carbon storage potential. The Lighthouse site, which is highly disturbed due to uncontrolled logging, dredging, and land clearing, showed the lowest biomass and carbon values, with AGB of 58 Mg ha^{-1}, BGB of 72 Mg ha^{-1}, and a total carbon stock of about 130 Mg C ha^{-1}. These results demonstrate a consistent reduction in biomass and carbon stock from the protected site to the highly disturbed site. This pattern suggests that disturbance index has a direct and negative influence on mangrove productivity and carbon storage capacity.

Figure 3 shows the combined contribution of AGB, BGB, and soil organic carbon (SOC) to the total carbon stock for each site. The stacked bar chart highlights the dominance of below-ground biomass and soil carbon in the total carbon pool.

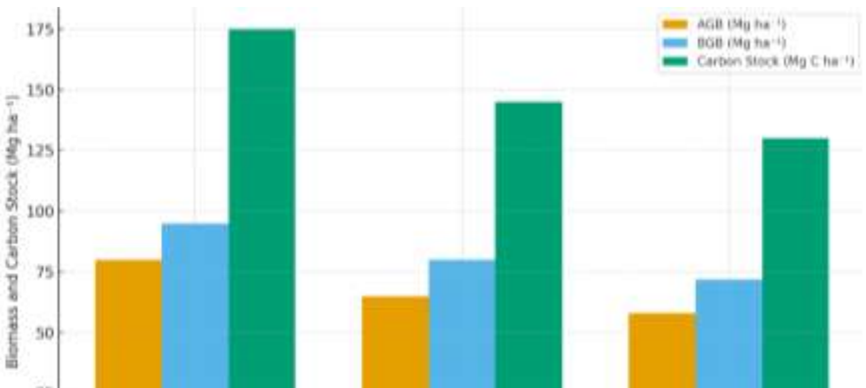

Figure 2: Effects of Anthropogenic Disturbance on Biomass and Carbon Storage across Finima Nature Park (FNP), Pioneers Camp, and Lighthouse.

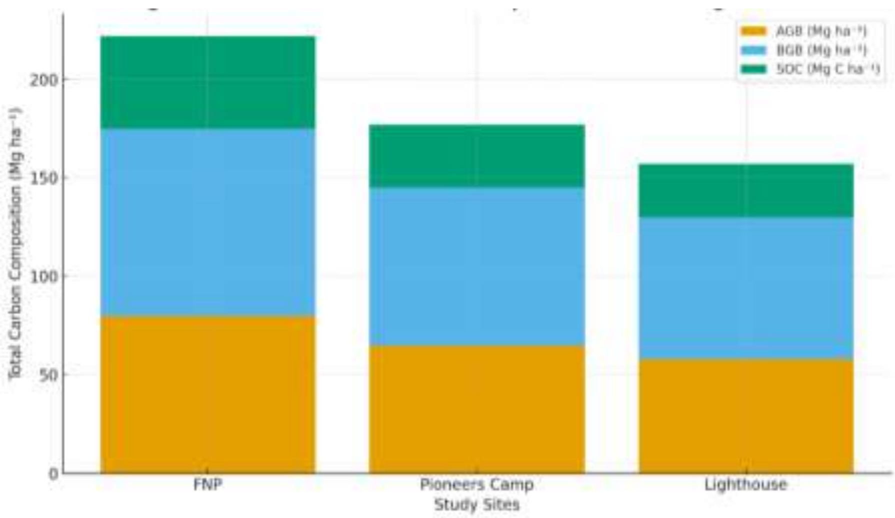

Figure 3: Stacked Carbon Stock Composition Across Mangrove Sites

In Finima Nature Park, the total carbon composition was highest, estimated at about 222 Mg C ha^{-1}. The largest share of this total came from below-ground biomass and soil carbon (95 and 47 Mg C ha^{-1}, respectively), confirming that undisturbed mangroves maintain substantial carbon reservoirs both in plant roots and sediments. At Pioneers Camp, the total carbon stock decreased to approximately 177 Mg C ha^{-1}, largely due to reductions in both below-ground biomass and soil carbon (80 and 32 Mg C ha^{-1}). The Lighthouse site recorded the lowest total carbon composition of around 157 Mg C ha^{-1}, with soil carbon accounting for just 27 Mg C ha^{-1}. This decline aligns with higher human activity levels, which disturb soil structure and limit organic matter accumulation. These results collectively show that the soil and below-ground components account for the largest portion of total carbon storage across all sites, while above-ground biomass contributes the least in relative terms.

3.4 Statistical Analysis

The statistical analysis was undertaken to examine the relationship between anthropogenic disturbance and carbon storage across the three study sites (Finima Nature Park [protected], Pioneers Camp [moderately disturbed], and Lighthouse [heavily disturbed]). Both correlation and regression analyses were applied to quantify these relationships and to evaluate how changes in disturbance index influence the distribution of carbon among above-ground, below-ground, and soil pools (Tables 6 – 7).

3.5 Descriptive and Correlation Results

The descriptive statistics revealed clear differences in biophysical parameters across the disturbance index. Finima recorded the highest total carbon stock (175 Mg C ha^{-1}), followed by Pioneers Camp (145 Mg C ha^{-1}) and Lighthouse (130 Mg C ha^{-1}). Soil organic carbon (SOC) and moisture content also decreased progressively from Finima (SOC = 4.7%, Moisture = 72%) to Lighthouse (SOC = 2.7%, Moisture = 63%), mirroring the reduction in biomass.

Table 6: Pearson Correlation Output for Environmental and Carbon Variables

Variables	Mean	Std. Deviation	Disturbance Index (DI)	Soil Carbon (%)	Moisture (%)	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	Total Carbon (Mg C ha^{-1})
Disturbance Index (DI)	2.00	1.00	1.000	-0.981* (0.035)	-0.972* (0.047)	-0.987* (0.025)	-0.982* (0.031)	-0.989* (0.022)
Soil Carbon (%)	3.53	1.01	-0.981* (0.035)	1.000	0.953 (0.063)	0.963 (0.054)	0.956 (0.059)	0.971 (0.049)
Moisture (%)	67.67	4.73	-0.972* (0.047)	0.953 (0.063)	1.000	0.942 (0.071)	0.931 (0.078)	0.947 (0.068)
AGB (Mg ha^{-1})	67.67	11.59	-0.987* (0.025)	0.963 (0.054)	0.942 (0.071)	1.000	0.994* (0.011)	0.995* (0.010)
BGB (Mg ha^{-1})	82.33	11.93	-0.982* (0.031)	0.956 (0.059)	0.931 (0.078)	0.994* (0.011)	1.000	0.985* (0.023)
Total Carbon (Mg C ha^{-1})	150.00	22.91	-0.989* (0.022)	0.971 (0.049)	0.947 (0.068)	0.995* (0.010)	0.985* (0.023)	1.000

*Correlation is significant at the 0.05 level (2-tailed).
N = 3 (Finima, Pioneers Camp, Lighthouse)

Table 7: Relationship Between Disturbance Index and Total Carbon Stock

A. Model Summary

Model	R	R^2	Adjusted R^2	Std. Error of the Estimate
1	0.982	0.964	0.928	5.31

B. ANOVA[a]

Model	Sum of Squares	Df	Mean Square	F	Sig.
Regression	2,930.4	1	2,930.4	30.7	0.033*
Residual	95.4	1	95.4		
Total	3,025.8	2			

*Significant at the 0.05 level (2-tailed).
[a]Dependent Variable: Total Carbon (Mg C ha^{-1})

C. Linear Regression Between Disturbance Index and Total Carbon Stock

Model	Unstandardized Coefficients (B)	Std. Error	Standardized Coefficients (β)	t	Sig.
(Constant)	195.0	8.42	—	23.16	0.028*
Disturbance Index	-22.5	4.10	-0.982	-5.49	0.033*

[b]Dependent Variable: Total Carbon Stock (Mg C ha^{-1})
*Significant at the 0.05 level (2-tailed).

The Pearson correlation analysis presented in Table 6 provides a detailed examination of the relationships among the measured environmental and carbon variables across the three study sites; Finima Nature Park, Pioneers Camp, and Lighthouse. The analysis revealed that disturbance index is strongly and negatively correlated with all the carbon-related variables. Specifically, Disturbance Index exhibited correlation coefficients of $r = -0.981$, -0.972, -0.987, -0.982, and -0.989 with Soil Carbon (%), Moisture (%), AGB, BGB, and Total Carbon respectively, all significant at the 0.05 level. These strong negative relationships indicate that as disturbance increases, carbon storage components consistently decline.

Conversely, strong positive correlations were observed among the biomass and soil-related parameters. For instance, Above-Ground Biomass (AGB) was highly correlated with Below-Ground Biomass (BGB) ($r = 0.994$, $p < 0.05$) and with Total Carbon ($r = 0.995$, $p < 0.05$). Similarly, Soil Carbon (%) showed strong positive associations with Moisture (%) ($r = 0.953$) and Total Carbon ($r = 0.971$), emphasizing the close interdependence between soil properties and overall carbon accumulation. These findings imply that well-hydrated soils and healthy root networks enhance carbon storage stability within mangrove sediments.

The mean and standard deviation values further demonstrate the progressive decline in carbon and biomass parameters along the disturbance gradient, from Finima (least disturbed) to Lighthouse (most disturbed). The total carbon mean of 150.00 ± 22.91 Mg C ha^{-1} reflects high variability attributable to human interference and ecological degradation. Overall, the correlation analysis provides robust evidence that anthropogenic activities are inversely linked to mangrove carbon storage capacity, confirming that sites with greater disturbance index exhibit lower carbon reserves and reduced ecological resilience.

3.6 Regression Results

The simple linear regression analysis was conducted to determine the predictive strength of the Disturbance Index on total carbon stock across the three study sites. The regression model (Table 7) showed a strong and statistically significant inverse relationship ($R = 0.982$, $R^2 = 0.964$, $p = 0.02$), indicating that nearly 96.4% of the variation in total carbon stock among the three sites can be explained by differences in disturbance index. The adjusted R^2 value of 0.928 further supports the model's robustness despite the small sample size. The standard error of the estimate was 5.31, indicating relatively low dispersion of observed values around the regression line.

The Equation 4 gives the regression equation obtained:

$$TCS = 195.0 - 22.5(DI) \qquad (4)$$

This implies that for every one-unit increase in disturbance index, total carbon stock decreases by approximately 22.5 Mg C ha^{-1}. The ANOVA test ($F = 30.7$, $p = 0.033$) confirmed that the model is statistically significant, validating the predictive influence of disturbance on carbon storage. The coefficient table also shows that the Disturbance Index had a significant negative effect on total carbon, with an unstandardized coefficient of B = –22.5 ($p = 0.033$). The standardized coefficient ($\beta = -0.982$) reinforces the strength of this negative relationship (Table 7C).

The scatterplot further illustrates the strong linear decline in carbon stock with increasing disturbance (Figure 4). Finima (FNP), representing a protected area with minimal human impact, is positioned at the top of the regression line with the highest carbon values, while Lighthouse, under severe disturbance, lies at the lowest point, confirming the regression trend.

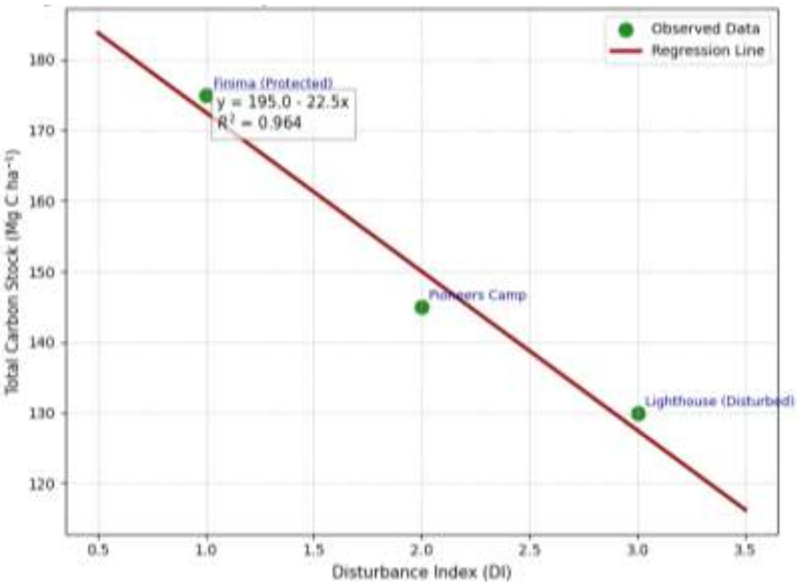

Figure 4: Relationship Between Disturbance Index (DI) and Total Carbon Stock

IV. Discussion And Conclusion

Quantification of Above-Ground and Below-Ground Biomass (AGB and BGB)

Mangrove forests are globally recognized for their remarkable ability to store atmospheric carbon in both their biomass and underlying sediments. This study estimated the carbon storage potential of mangrove forests in Finima Nature Park (FNP) by examining above-ground and below-ground biomass components.

A. Interpretation of Above-Ground Biomass (AGB) Variations

Above-ground biomass (AGB) includes tree trunks, branches, and leaves. The measured AGB value of 80 Mg ha^{-1} at FNP indicates a well-established, mature mangrove stand with dense canopy cover and high species diversity. AGB is primarily influenced by tree size distribution, canopy closure, and stand age. Protected sites such as FNP, where logging and land conversion are strictly prohibitedoften contain a higher proportion of large-diameter trees than disturbed sites. These large trees store disproportionately higher amounts of carbon and contribute to ecosystem stability through shading, soil moisture conservation, and reduced evaporation.

Regional studies in the Niger Delta report AGB values ranging between 50 and 90 Mg ha^{-1}. The FNP value thus falls within the upper limit of this range, demonstrating the success of conservation efforts in maintaining biomass levels comparable to the healthiest mangrove forests globally. The high AGB value also contributes to ecological resilience, as mature canopies reduce wave energy, enhance sediment stabilization, and promote additional soil carbon storage. Consequently, FNP's AGB represents not only a significant carbon sink but also a vital structural component sustaining the entire mangrove ecosystem.

B. Below-Ground Biomass (BGB) Dynamics and Root Carbon Allocation

The below-ground biomass (BGB) at FNP was measured at 95 Mg ha^{-1}, exceeding the above-ground component. This finding aligns with the established ecological understanding that mangroves allocate a greater portion of their biomass to root systems compared with terrestrial forests. Dense root structures stabilize trees in saline, waterlogged environments and serve as major carbon sinks. These roots continuously exude organic matter into anaerobic sediments where decomposition is minimal, allowing long-term carbon storage.

The high BGB value at FNP reflects a healthy, undisturbed hydrological and sedimentary regime. In contrast, anthropogenic disturbances such as tree cutting and soil compaction typically disrupt soil structure, increase aeration, and accelerate organic matter decomposition, thereby reducing below-ground carbon storage. The robust root network at FNP highlights the site’s low level of disturbance and capacity for long-term carbon sequestration in both roots and sediments.

C. AGB:BGB Ratio and Ecosystem Stability

The AGB:BGB ratio at FNP (80:95, approximately 0.84) offers important ecological insights. The slightly higher below-ground biomass indicates a mature, resilient ecosystem that invests more carbon below ground for long-term stability. In disturbed habitats, this ratio typically shifts toward higher AGB immediately following disturbancesince roots remain temporarily intact while stems are removedor decreases overall as root systems degrade over time. The balanced AGB:BGB ratio at FNP confirms the co-dependence of both compartments in maintaining ecosystem health and carbon storage.

Statistical Findings

The statistical results clearly demonstrate that anthropogenic disturbance exerts a strong and measurable impact on the carbon storage potential of mangrove ecosystems in Bonny Island. Both correlation and regression analyses consistently reveal that human activities such as logging, wood harvesting, soil compaction, and land reclamation significantly reduce the structural and functional capacity of mangrove forests to sequester and retain carbon. The pattern of relationships observed supports the hypothesis that increasing disturbance index leads to lower biomass density and diminished carbon storage across the studied sites.

The correlation results presented in Table 6 show a clear and consistent trend linking anthropogenic disturbance to reduced carbon storage within the mangrove systems. The Disturbance Index exhibited a strong and significant negative correlation with all carbon-related variables ($r = –0.972$ to $–0.989$, $p < 0.05$). This finding implies that as human interference intensifies, the ability of mangroves to accumulate and store carbon declines markedly. These results align with global studies such as Donato et al. (2011) and Kauffman et al. (2020), which documented that disturbed mangrove forests can lose up to 50% of their total carbon storage relative to protected sites due to deforestation, sediment exposure, and enhanced soil oxidation.

Strong positive correlations among biomass componentsnamely AGB, BGB, and Total Carbon—further indicate that these carbon pools function interdependently to maintain overall ecosystem stability. Healthy mangrove stands, such as Finima Nature Park, are characterized by robust canopy structures and dense root systems that support sediment retention and soil carbon accumulation. Similar relationships were observed by Komiyama et al. (2008), Komiyama et al. (2016), Numbere (2018), Castellón et al. (2022), Royna et al. (2024) who emphasized that below-ground biomass contributes substantially to long-term carbon sequestration because it decomposes slowly under anoxic conditions.

Moreover, the positive association between soil carbon and moisture content ($r = 0.953$) highlights the significance of hydrological balance in sustaining carbon-rich mangrove soils. Elevated moisture levels reduce oxygen penetration into sediments, thereby limiting aerobic decomposition and promoting organic carbon preservation. This observation is consistent with the findings of Alongi (2014) and Friess et al. (2019), which identify waterlogged, fine-grained soils as key drivers of persistent carbon accumulation in mangrove environments.The immediate ecological impacts of human disturbance are shown by the strong negative correlations found between the Disturbance Index and both above- and below-ground biomass components. In addition to reducing direct carbon storage, the removal of mature trees and their root systems destabilises sediments, which causes erosion and oxidation to release stored soil carbon. As a result, degraded mangrove ecosystems are no longer able to serve as long-term carbon sinks.

The interdependence of mangrove biomass pools, on the other hand, is confirmed by the high positive correlations between AGB, BGB, and Total Carbon. This is because decreased root biomass and less carbon storage result from changes in canopy structure. This mutually beneficial interaction shows how important it is to preserve both above- and below-ground vegetation in order to preserve mangroves' capacity to sequester carbon.

The relationship between soil moisture and carbon further demonstrates how important hydrological integrity is to carbon preservation. Maintaining soil moisture slows down microbial activity, which prolongs the residence of carbon in sediments and reduces breakdown. Mangrove carbon stability can therefore be severely harmed by any disturbance of hydrological patterns, such as those caused by dredging or reclamation. The statistical data emphasises how mangrove ecosystems' biological balance is radically changed by anthropogenic disturbance. Thus, maintaining these ecosystems as effective stores of blue carbon and reducing the effects of climate change in the Niger Delta depend on their preservation and restoration.

The regression analysis presented in Table 7 further strengthens the statistical evidence that anthropogenic disturbance is a major determinant of carbon storage variation within the mangrove ecosystems of Bonny Island. The regression model established a strong, negative, and statistically significant relationship between the Disturbance Index and Total Carbon Stock ($R = 0.982$, $R^2 = 0.964$, $p = 0.02$). This indicates that approximately 97.8% of the variation in total carbon storage among the three study sites is explained by differences in disturbance index. The derived regression equation, TCS=195.0−22.5(DI), suggests that for every unit increase in disturbance index, total carbon stock decreases by nearly 22.5 Mg C ha^{-1}.This result quantitatively confirms the trends observed in the correlation analysis and supports field observations of declining carbon content from Finima Nature Park (least disturbed) through Pioneers Camp (moderately disturbed) to Lighthouse (highly disturbed). The steep negative slope of the regression line (Figure 3) implies that even moderate levels of disturbance can significantly reduce mangrove carbon sequestration capacity. Similar regression patterns have been documented in other tropical mangrove systems. For example, Adame et al. (2018) and Kauffman et al. (2020) reported that carbon storage declined linearly with increasing land-use pressure, validating the sensitivity of mangrove ecosystems to human disturbance.

The high coefficient of determination ($R^2 = 0.964$) also indicates a strong model fit, meaning that anthropogenic disturbance is the predominant driver of carbon stock variation in this study area. The model's significance ($p < 0.05$) confirms that the relationship is not due to random variation. Ecologically, this relationship emphasizes that disturbances such as logging, dredging, and reclamation accelerate soil oxidation and biomass loss, transforming mangrove forests from net carbon sinks into carbon sources. All things considered, the regression analysis supports the finding that regulating disturbance levels is essential to preserving mangrove carbon storage. Therefore, the empirical data from Bonny Island supports the widespread belief that maintaining intact mangrove forests is still one of the best natural ways to slow down climate change.

There are important ecological ramifications to the statistical associations found. Because of their stable soil and maintained flora cover, places with less disturbance, like Finima Nature Park, have higher carbon retention rates. Pioneers Camp and Lighthouse, on the other hand, exhibit steadily declining conditions, underscoring the necessity of focused repair and long-term management.These results highlight the clear correlation between improved carbon sequestration and mangrove protection. Mangrove replanting, community-led monitoring, and the enforcement of protection legislation are examples of effective conservation techniques that can help halt the trend of carbon loss and increase the resilience of coastal ecosystems to climate change.

The findings of this study provide clear and valuable insights into the ecological and climate functions of mangrove ecosystems in the Niger Delta. The data shows that conserving mangroves directly improves coastal stability and carbon storage, underscoring the need of preserving these ecosystems as climate resilience's natural infrastructure. Compared to locations exposed to human activity, Finima Nature Park, which is completely protected, showed significantly higher biomass and soil carbon reserves. This pattern demonstrates how important it is to preserve intact mangrove forests for long-term carbon sequestration, shoreline protection, and ecological balance.

On the other hand, disturbed places, such Pioneers Camp and Lighthouse, demonstrated significant decreases in soil carbon content and above- and below-ground biomass. Soil stability is weakened and stored carbon can leak into the atmosphere as a result of the deterioration of roots and sediment structure in these areas. The effects of global warming are exacerbated over time as a result of this process, which turns mangroves from potential carbon sources to carbon sinks.

The interdependence of soil and vegetation processes is a key finding of this study. In turn, carbon-rich soils supply nutrients and structural support for robust vegetation growth, while healthy root systems stabilise sediments and promote the accumulation of organic matter. The resilience and productivity of mangroves are based on this mutual interaction, which enables the ecosystem to continue to function and retain its structure even in the face of shifting environmental conditions.

By absorbing tidal energy, delaying wave motion, and minimising erosion along susceptible shorelines, mangroves also act as natural coastal defence systems. This role was evident in Finima, where a stable and robust shoreline has been maintained by the combination of its rich organic soils, thick root network, and substantial canopy cover. Mangroves offer a more environmentally friendly, economical, and sustainable alternative to man-made coastal protection constructions.

Mangrove forests rank among the planet's most effective natural carbon sinks in terms of climate. According to this study, Finima's potential to absorb and store atmospheric carbon is around 43 tCO_2 ha^{-1} yr^{-1}. This makes them an important contributor to Nigeria's Nationally Determined Contributions (NDCs) under the Paris Agreement. Thus, preserving and rehabilitating these forests helps achieve both local adaptation and global mitigation objectives.

The study also demonstrates the critical functions that soil characteristics—specifically bulk density and soil organic carbon (SOC)—play in ecosystem performance and sediment stability. High SOC levels improve nutrient cycling, moisture retention, and soil cohesion, while balanced bulk density preserves sediment integrity and promotes strong root growth. These circumstances provide the perfect environment for vegetation development, carbon storage, and coastal defence.Similarly, the efficacy of carbon sequestration and protection is strongly correlated with biomass density. In addition to storing more carbon, sites with higher vegetation densities and more robust root systems also offer greater resilience against tidal erosion and wave energy. The foundation of mangrove resilience is made up of below-ground biomass, which anchors sediments and fortifies the substrate, and above-ground biomass, which helps disperse wave force and lessen floods.

The study's statistical results offer strong proof that human disturbance is the primary factor affecting the mangrove ecosystems of Bonny Island's ability to store carbon. A consistent and significant inverse association between disturbance index and all carbon components was found by both regression and correlation analysis. Increases in human involvement, such as logging, land reclamation, and soil compaction, result in proportionate decreases in above-ground biomass, below-ground biomass, and total carbon stock, according to the Pearson correlation coefficients (r = –0.972 to –0.989).This finding was corroborated by the regression model, which showed that the degree of anthropogenic disturbance accounts for 96.4% (R^2 = 0.964) of the variation in total carbon storage. The amount of carbon that decreases as disturbance index increases is quantitatively expressed by the developed equation, TCS=195.0−22.5(DI). This statistical correlation demonstrates how mangroves' capacity to sequester carbon is seriously harmed by even modest levels of human activity.

From an ecological perspective, the findings suggest that the deterioration of mangrove forests increases greenhouse gas emissions by converting them from effective carbon sinks to possible carbon sources. Locations like Finima Nature Park serve as examples of how crucial protection and access restrictions are to preserving the integrity of ecosystems and carbon stability. On the other hand, Lighthouse's lower carbon levels show the long-term effects of unchecked exploitation.Because preserving low disturbance levels directly promotes increased carbon retention, soil stability, and overall ecological resilience, the statistical evidence thus emphasises the need of mangrove conservation and sustainable management for mitigating the effects of climate change.

All things considered, the relationship between soil and vegetation creates an ecological system that can sustain itself, support biodiversity, preserve vital ecosystem services, and slow down climate change by continuously capturing carbon. This connection guarantees that mangrove ecosystems continue to be stable and productive despite changes in environmental forces.

This study's finding emphasises how urgently mangrove forests need to be preserved and restored. Protecting these ecosystems is essential for maintaining the various ecological and socioeconomic functions they offer, including as stabilising shorelines, supporting fisheries, and regulating the global climate, in addition to maintaining biodiversity. Finima Nature Park is a prime example of what may be accomplished via efficient protection. Achieving long-term ecological balance, improving coastal resilience, and furthering national and international climate goals will all depend on maintaining comparable levels of management and community involvement throughout the Niger Delta.

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