

Assessment of Impacts of Mangrove Cover Changes on the Greenhouse Gas Emissions in the Niger Delta Region of Nigeria

ABSTRACT

The mangrove vegetation within the Niger Delta region of Nigeria is ravaged by anthropogenic practices including but not limited to rapid urbanization, aquaculture expansion and oil exploration which penultimately distorts the biodiversity of both the mangrove and marine environments, culminating in the loss of structural and functional integrity of these ecosystems, specifically their role in climate change regulation.

Aim: The study aimed at assessing the changes in mangrove covers from 1987 to 2022 in the study area as well as examining the changes in GHGs emissions resulting from the mangrove changes.

Methodology: The methodology adopted a remote sensing-based research design utilizing satellite imagery to analyze temporal changes in mangrove cover and evaluated their association with climate variables such as CO₂ emissions and LST of the study area. Each satellite image geo-referenced in ArcGIS 10.8 & LULC changes calculated using geometry module of ArcGIS 10.8. NDIR spectroscopy was used in examining the variation in GHGs emissions.

Result: the data obtained revealed mangrove reduction from 12,991 km² in 1987 to 9,089km² in 2022 resulting in the loss of 3,904.00 km² of mangrove forest. The reduction resulted in increased CO₂ emissions from 370.70 ppm to 403.29 ppm between 1987 and 2022. These results illustrate a clear link between mangrove cover change and CO₂ emissions, highlighting the critical role mangroves play in regulating climate change.

Conclusion: The study was able to show that significant losses in mangrove cover have been closely associated with increased CO₂ emissions, thus reflecting the vital role these ecosystems play in carbon sequestration which underscores the importance of preserving these vital ecosystems to mitigate local and global climate impacts.

Keywords: *Niger Delta, Mangrove Cover, Greenhouse gases*

1. INTRODUCTION

Mangroves are characterized by their high productivity (Komiya *et al.*, 2008) and capacity to store large amounts of organic carbon in its soils (Donato *et al.*, 2011; Nellemann *et al.*, 2009). The carbon

accumulation in its soils is a function of the inputs of organic carbon compounds, formed basically by photosynthetic processes sequestering atmospheric CO₂, and the losses caused by decomposition, erosion and leaching (Stockmann *et al.*, 2013). The organic compounds enter the edaphic system as litter, decaying roots, root exudates, and microbial biomass, which are decomposed by the activity of micro and mesofauna (Nelson and Oades, 1998).

Mangroves play a crucial role in mitigating climate change by removing carbon dioxide from the atmosphere and storing it in their biomass and sediments. Protecting and restoring mangrove forests is therefore considered an important strategy for climate change mitigation. Mangroves have been identified as blue carbon ecosystems that are natural carbon sinks (Donato *et al.*, 2011; Lovelock *et al.*, 2020; Murray *et al.*, 2011). These carbon rich ecosystems store carbon in both aboveground and belowground carbon pools and have a mean global ecosystem carbon stock of 939 Mg C ha⁻¹ (range 856–1023 Mg C ha⁻¹) of which 49%–98% is stored in the soil (Alongi, 2012; Donato *et al.*, 2011; Kauffman *et al.*, 2014; Sanderman *et al.*, 2018). Storage of carbon by coastal wetland ecosystems (such as mangroves) can be managed (e.g., conserved or restored) to assist in reducing atmospheric CO₂ (Pendleton *et al.*, 2012; Windham-Myers *et al.*, 2019).

Emissions of carbon dioxide (CO₂) and methane (CH₄) by mangrove sediments are potential sources of greenhouse gas to the atmosphere and as such may contribute to global climate change (Barnes *et al.*, 2006). On the other hand, the high primary production by mangrove trees, accretion and permanent storage of organic carbon in sediments point to the fact that many mangrove environments are actually sinks of atmospheric CO₂ (Alongi 2012). There are, however, large geographical differences in published attempts to estimate mangrove carbon gas balance caused by variations in factors such as geomorphology, freshwater input and degree of eutrophication (Alongi *et al.* 2014). Furthermore, it is important not only to consider the carbon balance in terms of CO₂ because CH₄ has about 20 times greater global warming potential than CO₂. CH₄ can be a major product of sediment carbon mineralization (Canfield, 2004) and as such a potential greenhouse gas emitted from mangrove ecosystems (Barnes *et al.* 2006).

Historic rates of mangrove deforestation posed a serious risk of significant GHG emissions and since the 1950's it has been estimated that up to 50% of the world's mangroves have been deforested, largely due to land-use change (Alongi, 2002). Despite estimates of recent global mangrove loss slowing to 4.0% of global coverage between 1996 and 2016 (Richards *et al.*, 2020), it has been estimated that > 300 million Mg of CO₂e were emitted as a result of mangrove deforestation between 2000 and 2012 (Hamilton and Friess, 2018). Between 2000 and 2016, 87% of mangrove loss in the West Coral triangle, where the vast majority of the world's mangroves organic carbon is stored, was due to agriculture/aquaculture land-use conversion (Adame *et al.*, 2021). Mangrove conservation and restoration programs on a national scale have been identified as an efficient means of offsetting GHG emissions (Murdiyarso *et al.*, 2015; Taillardat *et al.*, 2018; Cameron *et al.*, 2019), although the prevention of further forest loss, by far, outweighs gains from restoration (Kauffman *et al.*, 2017).

In mangroves, due to the frequent flooding event by seawater, organic matter decomposition occurs by reducing other electron acceptors substituting the O_2 (i.e., $O_2 \rightarrow NO_3^- \rightarrow Mn$ oxyhydroxides $\rightarrow Fe$ oxyhydroxides $\rightarrow SO_4^{2-} \rightarrow CO_2$), decreasing the decomposition rate as a result of the lower energetic yield (Alongi *et al.*, 2009). Because of the combination of high biomass production and low decomposition rates, mangroves, and other coastal wetlands have been denominated as “Blue Carbon sinks” emphasizing the important role that these ecosystems perform in sequestering atmospheric CO_2 (Duarte *et al.*, 2005; Mcleod *et al.*, 2011).

CO_2 production in mangrove soils refers to microbial activity during organic matter degradation, mainly, and root respiration (Lovelock *et al.*, 2011). The CO_2 flux to the atmosphere occurs when microorganisms oxidize the organic carbon using O_2 , NO_3^- , Mn^{4+} , Fe^{3+} , and SO_4^{2-} as electron acceptors. On the other hand, CH_4 production occurs in flooded areas using CO_2 or other methyl compounds under extreme anoxic conditions (Kristensen, 2007; Yu *et al.*, 2009). Besides, N_2O is produced by nitrification processes, converting ammonium to nitrate under aerobic conditions or by a denitrification process that involves anaerobic reduction of nitrate to N_2 (Chauhan *et al.*, 2016). Since the GHG emission is performed through microbial processes, the edaphic and climatic factors (e.g., redox potential; organic carbon content; salinity and temperature) may affect these emissions (Chen *et al.*, 2010).

Despite its ecological importance, including its role in sequestering atmospheric CO_2 , the mangrove forests are declining to extinction due to anthropogenic impacts that directly remove the vegetation, e.g., aquaculture, urbanization and coastal landfill (Duke, 2016). Globally, the mangroves occupy 0.7% of the tropical forest area, but their destruction currently adds 10% to global CO_2 release from tropical deforestations (Alongi, 2014). Other activities (i.e., shrimp farming and eutrophication) are related to nutrient-rich effluent release, which promotes changes in the soil characteristics and stimulates organic matter decomposition, increasing CO_2 fluxes (Chen *et al.*, 2010). In addition, mangroves can be an important source of CH_4 and N_2O to the atmosphere (Barnes *et al.*, 2006; Kristensen, 2007) contributing to global climatic changes due to its warming potential (Chauhan *et al.*, 2016).

While the potential for GHG emissions from mangrove deforestation are well documented (Lovelock *et al.*, 2011; Kauffman *et al.*, 2014; Lang'atet *et al.*, 2014; Atwood *et al.*, 2017; Hamilton and Friess, 2018), the effects of climate change on global mangrove carbon stocks are less frequently addressed (Adame *et al.*, 2021) and are therefore a priority research area for blue carbon science (Macreadie *et al.*, 2019). Change in climatic regimes could also prove a significant factor in changing overall stocks in mangroves through altering forest biomass and productivity and its subsequent contribution to soil C stocks and soil sequestration rates (CSR).

Consequently, Chattinget *et al.*, (2022) conducted a study where they modelled the effects of climate change on future carbon stocks and soil sequestration rates (CSR) under two climate scenarios (“business as usual”: SSP245 and high-emissions: SSP585). Model results were contrasted with CO_2 equivalents (CO_2e) emissions from past, present and future rates of deforestation on a country specific scale. For carbon stocks, they found out that climate change will increase global stocks by

~7% under both climate scenarios and that this gain will exceed losses from deforestation by the end of the twenty-first century, largely due to shifts in rainfall. Major mangrove-holding countries Indonesia, Malaysia, Cuba, and Nigeria will increase national carbon stocks by > 10%. Under the high-end scenario, while a net global increase is still expected, elevated temperatures and wider temperature ranges are likely to increase the risk of countries' carbon stocks diminishing.

For CSR, Chatting *et al.*, (2022) reported that there will likely be a global reduction under both climate change scenarios such that 12 of the top 20 mangrove-rich countries will see a drop in CSR. Modelling of published country level mangrove deforestation rates showed that emissions have decreased from 141.4 to 6.4% of annual CSR since the 1980's. Projecting current mangrove deforestation rates into the future resulted in a total of 678.50 ± 151.32 Tg CO₂e emitted from 2012 to 2095. Reducing mangrove deforestation rates further would elevate the carbon benefit from climate change by 55–61%, to make the proposition of offsetting emissions through mangrove protection and restoration more attractive. These results according to Chatting *et al.*, (2022) demonstrated the positive benefits of mangrove conservation on national carbon budgets, and they identified the nations (e.g. Indonesia) where incorporating mangrove conservation into their Nationally Determined Contributions offers a particularly rewarding route toward meeting their Glasgow Agreement commitments.

The study aimed to evaluate factors influencing greenhouse gas (especially CO₂) emissions from Niger Delta Mangrove Forests in Southern Nigeria under different anthropogenic activities, in order to better comprehend the role of these endangered ecosystems for GHG emissions and carbon sequestration.

2. STUDY AREA

Niger Delta Region is situated between longitude (5.05°E-7.17°E) and latitude (4.15° N-7.17°N) in the southern part of Nigeria and bordered to the south by the Atlantic Ocean and to the East by Cameroon. It occupies a total land area of 75,000 square kilometres, and it is the world's second largest delta with a coastline of about 450 km (Awosika, 1995). Niger Delta is composed of 9 out of 36 states in Nigeria, (Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Ondo, Imo and Rivers), and has 185 out of 774 local government areas. The predominant settlement type in the Niger Delta is small and scattered hamlets (Akpan *et al.*, 2017). The vast majority of settlements comprise largely rural communities in dispersed village settlements. In total, there are 13,329 settlements in the Niger Delta Region (Enaruvbe and Atafo, 2014). Extrapolations from the 1991 National Population Census showed that at a growth rate of 2.9% the population of the Niger Delta Region by 2004 was about 30 million. There is an estimated population of about 41.5 million (about 22% of Nigeria's population of 200 million) and characterized by high ethnic and cultural diversity (NPC, 2023). The region has a maximum elevation of about 3m above mean sea level on the sandy barrier islands that border the

sea and the Montana zone, is confined to the northeastern part of Cross River State being a high-altitude area approximately 900m to 1500m above sea-level (Dangana, 1981).

The study area is the Mangrove Forest in the Niger Delta Region, located along the Gulf of Guinea in the South-South Geopolitical Zone of Nigeria. It extends along the Gulf of Guinea, from the mouth of the Benin River for a distance of about 450 km, to its eastern flank at the Calabar Estuary in Cross River State. It lies between latitudes 4° 16' 22" and 5° 33' 49" N and longitudes 5° 3' 49" E and 7° 35' 27" E (**Fig. 1**). The Niger Delta Mangrove Ecosystem is the third largest mangrove in the world, comprising some 36,000 km² in area (Wang *et al.*, 2016). It is spread across Ondo, Edo, Delta, Bayelsa, Rivers, Akwa-Ibom and Cross Rivers (James *et al.*, 2013). According to Ayanlade (2012) Niger Delta has four ecological zones namely the mangrove vegetation, freshwater swamp, rainforest, and derived savannah.

The Nigerian coastal zones have a tropical climate with rainy and dry seasons (Nwilo and Badejo, 2006). The Niger Delta areas generally have an equatorial climate on its southern coast and subequatorial climate in the north. The monthly mean temperature ranges between 25 °C and 29 °C, while the annual precipitation ranges between 2000 mm and 4000 mm, with relative humidity being above 70%. The rainy season in the Niger Delta lasts from March to October, with a little dry spell experience during the August break due to monsoon winds from the southwest that carries moisture from the ocean into the hinterland. The dry season lasts from November to February with harmattan experienced between December and February that is caused by tropical continental air mass from the north (Ohwo, 2015). The coastline is generally classified into four geomorphological units viz: The Strand coast, the Mud coast, the Barrier Lagoon coast and the Niger Delta (Agumagu, 2015). Creeks, estuaries, and rivers cover an estimated 2370 km² of the Niger Delta land; stagnant swamps cover approximately 8600 km², while the mangrove swamp with about 1900 km² is considered Africa's largest (Uyigue and Agho, 2007).

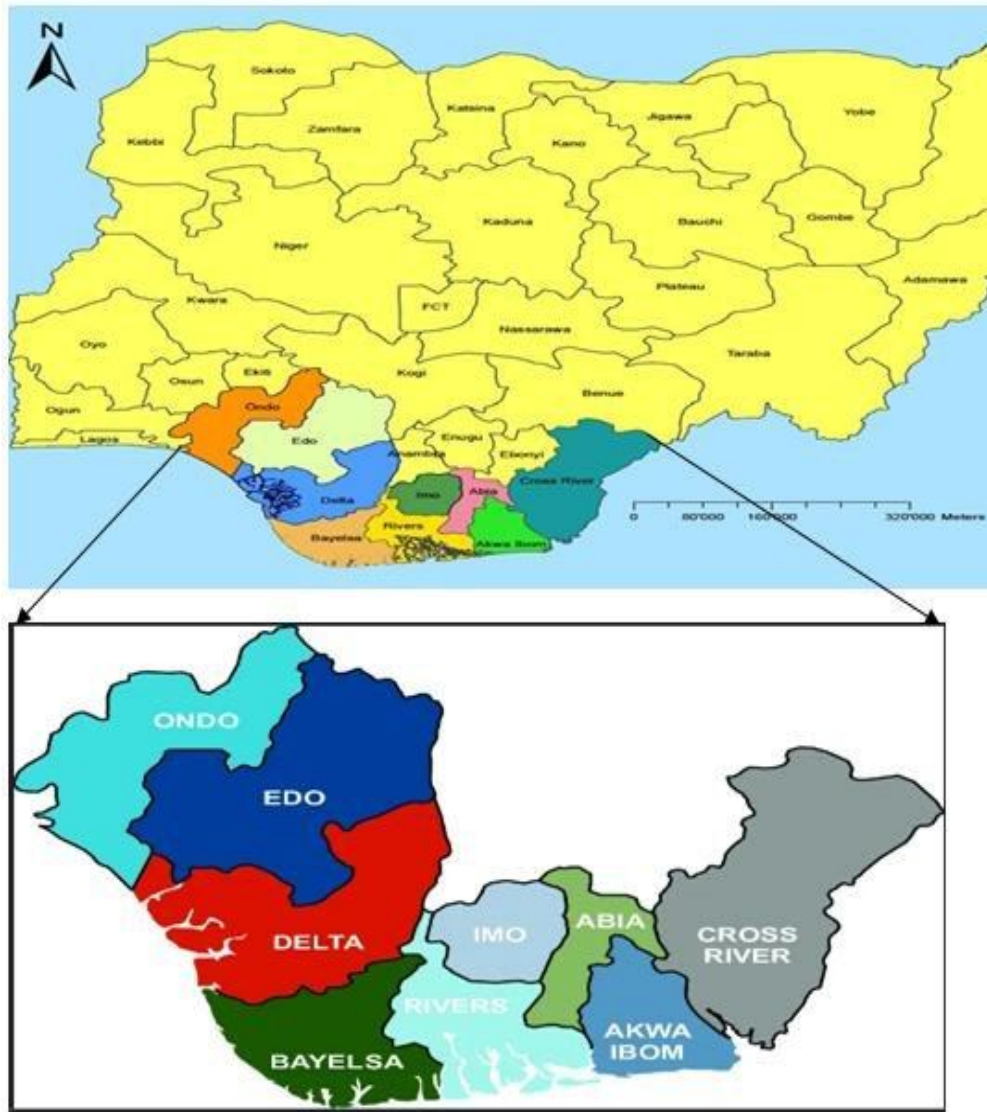


Figure 1: Map of Nigeria Showing Niger Delta Region

3. METHODOLOGY

The study adopted a remote sensing-based research design using satellite imagery to analyse temporal changes in mangrove cover and evaluated their association with climate variables such as variation in the CO₂ emissions and land surface temperature (LST) of the study area.

3.1 Data Types and Sources

Data was generated mostly from Secondary sources (satellite images downloads). However, primary data was also generated from directly from the impacted coastal communities, impacts of forest depletion on farming, impacts of nypa palm invasion on the economy and livelihood, impacts of climate change on farming/agricultural pattern.

Table 1. Data acquisition, source and magnification

Data Type	Specific Data	Source	Resolution
Satellite Imagery	Landsat, Sentinel, MODIS	USGS, ESA, NASA	10m-30m (MODIS: 250m)
Climate Data	Temperature, Precipitation	ERA5, MODIS, Global Carbon Project	0.25° - 0.5° grid
Carbon Sequestration	Biomass, CO ₂ concentrations	Global Mangrove Watch, Global Carbon Project	Variable
Socioeconomic Data	Population, land use, oil facilities	National Population Commission, World Bank, FAO	Variable

These data types and sources provided a robust foundation to examine the impacts of mangrove cover changes on climate variables, offering both spatial and temporal depth for meaningful analysis.

3.2 Population of the Study

For the study, population refers to the geographic area and environmental data points relevant to mangrove cover and climate change indicators within the Niger Delta Region. Thus, the population for the study comprises: Geographic Extent (all mangrove cover areas within the Niger Delta Region which includes nine states of Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo, Rivers, and Abia, and encompasses significant mangrove forests); Temporal Scope (annual or multi-year data from 1987 to 2022) as well as Data Variables (pixels or grid cells in satellite imagery representing mangrove areas, and associated climate data (temperature, carbon sequestration, precipitation) within these areas).

3.3 Sample technique and Sample Size

A combination of systematic sampling and stratified sampling techniques were used in order to allow for effective temporal and spatial analysis of mangrove cover changes and their climate impacts. Based on the study population and the sample technique used, the sample size for the study included:

- **Temporal Sample Size:** Approximately 20 time points across the 1987-2022 period.
- **Spatial Sample Size:** Around 1,500-3,000 pixels per image for mangrove areas (stratified by ecological zone), with a denser sampling in high-change zones using higher-resolution data where feasible.

3.4 Data acquisition and analysis

Landuse/cover images of different periods in Niger Delta Region were captured from the Landsat Thematic Mapper (TM) imagery of 30m x 30m for 1987, 2002, 2012, and 2022. Each image was geo-referenced in ArcGIS 10.8 to Universal Transverse Mercator, Zone 32N (WGS 84). Composite analysis was carried out for the bands of each image in each period in order to produce a false composite imagery in ArcGIS 10.8.

From the ground-truthing of the land use/cover types in the study area with additional information from the satellite imageries, an image classification analysis was carried out to classify the spectral reflectance into different major landuse types as found during the reconnaissance survey. Six major classes namely vegetation, farmland, built-up area, bare land, water body, and mangrove were identified and their descriptions tabulated. These classes are similar to the landuse/cover categories in the Niger Delta acknowledged by Ayanlade (2012). The spatial coverage of each landuse/cover type was determined in squared kilometers using the calculated geometry module of ArcGIS 10.8. These images were used to classify changes in mangrove extent.

3.5 Image Processing and Classification

- i. Supervised or unsupervised classification methods were used to categorize pixels in the satellite imagery into land cover classes, including mangrove forest, vegetation, farmland, built-up area, bare land and water body.
- ii. Ancillary data and ground truthing were incorporated to improve classification accuracy and resolve class ambiguities.

3.6 Change detection analysis

Change detection analysis was performed using land use/cover map in 1987, 2002, 2012, and 2022. Change detection refers to the process of identifying differences in the state of land features by observing them at different times. In post-classification change detection, the images from each time period were classified using the same classification scheme into a number of discrete categories (i.e., land cover types) (Nguyen *et al.*, 2013). Quantitative analysis of landuse/cover between different dates was conducted to detect the change.

3.7 Annual rate of change in land use/cover

The percentage change in spatial coverage in percentage (%) for each land use type was calculated as a percentage increase or decrease in land use spatial coverage of the previous period for each land use type.

3.8 Formulas:

- a. Annual Rate of Change (km^2 per Year) = Observed Land Use Change in km^2 /No. of Yrs. Taken for the Change to Occur.
- b. Percentage Change in Area (%) = $\frac{\text{New Value} - \text{Old Value}}{\text{Old Value}} \times 100$

Where: New Value is the Current or Latest Land Cover Area, Old Value is the Previous or Original Land Cover Area.

- c. Total Change = $\text{New Value} (\text{km}^2) - \text{Old Value} (\text{km}^2)$.
- d. Annual Rate of Change = $\frac{\text{Total Change}}{\text{Old Value}/\text{No. of Years}} \times 100\%$.

Note: Negative result indicates mangrove loss or decline. The positive result indicates mangrove gain or increase.

3.9 Non-Dispersive Infrared (NDIR) spectroscopy: This is a commonly used method in the field of gas sensing (Goldenstein *et al.*, 2017) and as such, NDIR was used for measuring emissions of greenhouse gases in the research work. Greenhouse Gases Observing Satellite (GOSAT) with passive remote sensing was used to measure greenhouse gas concentrations from space within the study area. Quantitative analysis using spectroscopy was based on the Beer–Lambert law, which demonstrates a change in the radiant power when the radiant power in a beam of electromagnetic radiation passes through a cell containing a homogeneous mixture. The Beer–Lambert law can be expressed as follows:

$$T = P(\lambda) / P_0(\lambda) = 10^{-\epsilon(\lambda) \cdot l \cdot c}$$

Where P [W] denotes the transmitted light radiant power of the cell,

P_0 [W] denotes the initial light radiant power,

T denotes the transmittance,

$\epsilon(\lambda)$ cm^2/mol denotes the molar absorption coefficient at wavelength, λ ,

l [cm] denotes the OPL, and c mol/cm denotes the molar concentration (Mayerhöfer *et al.*, 2016).

The transmittance (T) is the ratio of the initial light radiant power (P_0) to the vacant cell and light radiant power (P) transmitted through a gas cell filled with absorbing gas. Transmittance is complementary to the molar absorption coefficient, optical path length, and molar concentration. A long OPL enhances the sensitivity to perform trace-level detection in the case of trace-level concentration.

4. RESULTS AND DISCUSSION

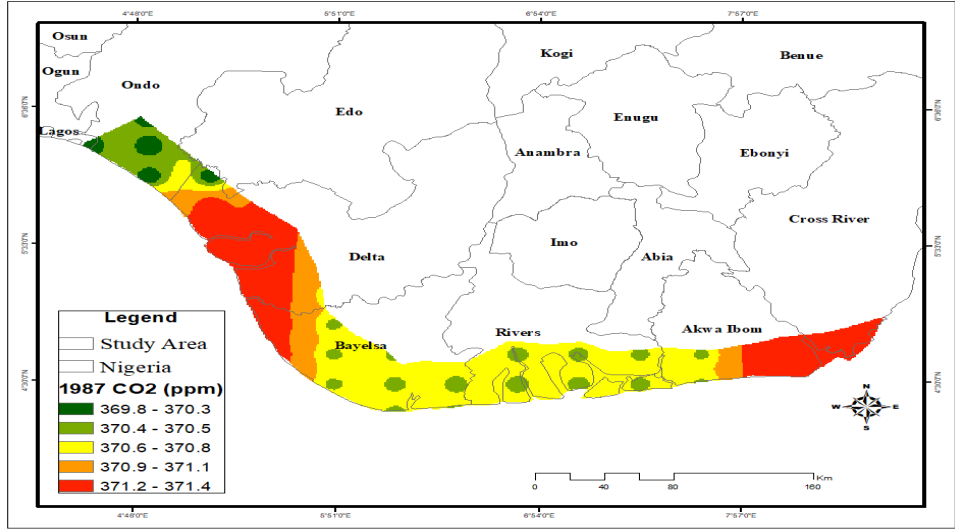


Figure 2. Greenhouse Gasses Emission Map (1987)

Figure 2 shows the concentration of CO₂ in the atmosphere within the study area in the year 1987. As at 1987, the lowest concentration of CO₂ was 369.8 ppm while the highest concentration of CO₂ was about 371.4 ppm distributed across the study area.

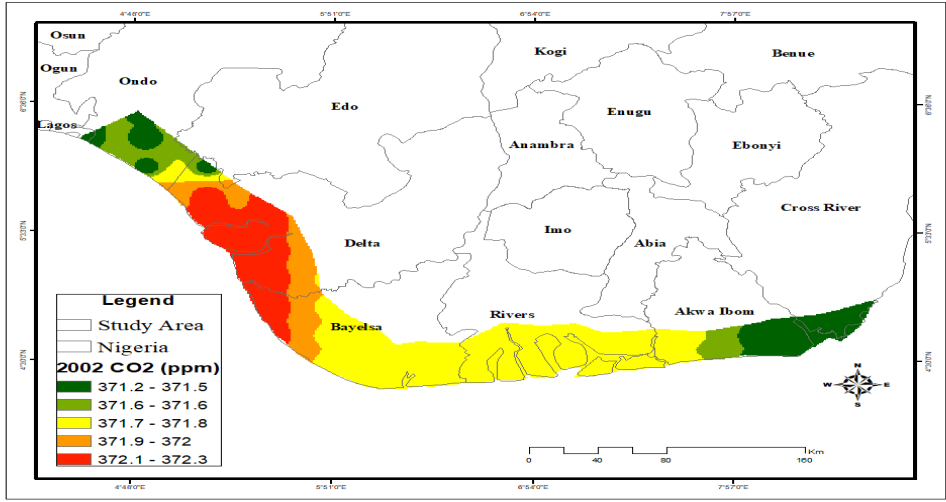


Figure 3. Greenhouse Gasses Emission Map (2002)

Year 2002 showed increase in the concentration of CO₂ as compared to the year 1987 with the minimum concentration of about 371.2 ppm while the maximum concentration was about 372.3 ppm.

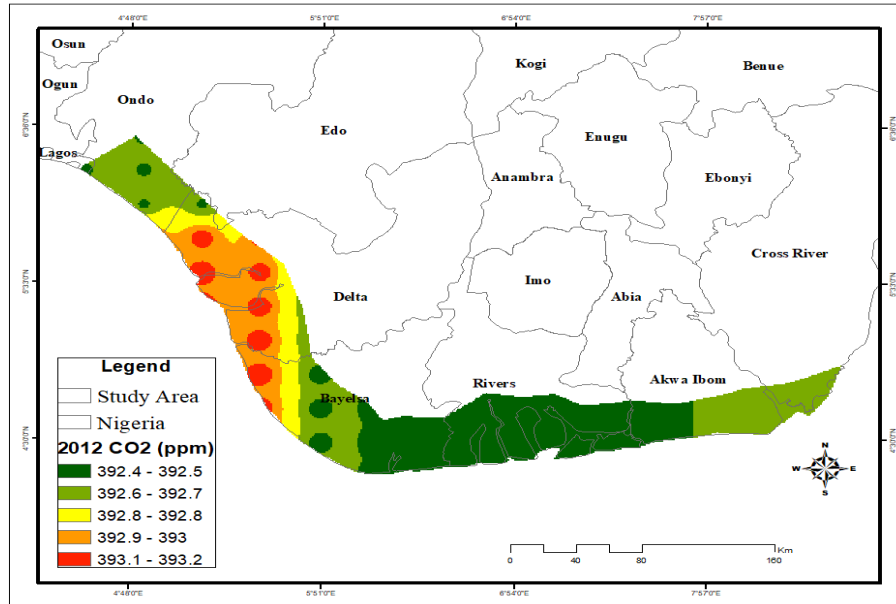


Figure 4. Greenhouse Gasses Emission Map (2012)

In the year 2012, the concentration of CO₂ further increases as compared to the year 1987 and 2002 with the minimum concentration of about 392.4 ppm while the maximum concentration was about 393.2 ppm.

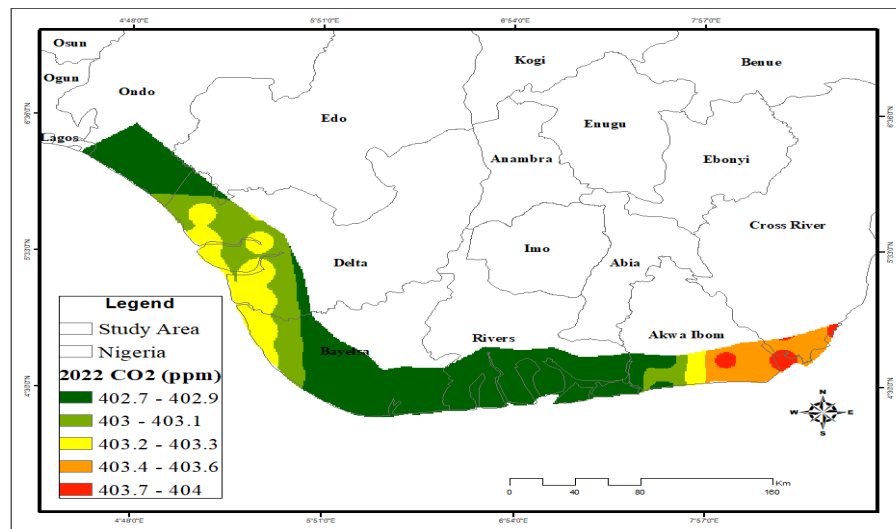


Figure 5. Greenhouse Gasses Emission Map (2022)

A further increase in the concentration of the atmospheric CO₂ as compared to the year 1987, 2002 and 2012 with the minimum concentration of about 402.7 ppm was captured (figure 5) while the maximum concentration was about 404.0 ppm.

The concentration of carbon dioxide (CO₂) in the atmosphere is typically measured in parts per million (ppm). This unit indicates the number of CO₂ molecules per million molecules of air. For example, if the CO₂ concentration is 420 ppm, it means there are 420 molecules of CO₂ in every million molecules of air.

Table 2. CO₂ Emissions from Change in Mangrove Cover of Study Area (1987 – 2022)

Year	Two Limits of Emissions (ppm)	Average Emission (ppm)	Area Km ²	%
1987	369.8 – 370.3	370.05	583.88	3
	370.4 – 370.5	370.45	2,803.48	13
	370.6 – 370.8	370.7	9,293.90	42
	370.9 – 371.1	371	2,492.95	11
	371.2 – 371.4	371.3	6,693.79	31
Total	Overall Average for 1987 = 370.70		21,868.00	100
2002	371.2 – 371.5	371.35	3,039.65	14
	371.6 – 371.6	371.6	1,902.52	9
	371.7 – 371.8	371.75	10,223.29	47
	371.9 – 372.0	371.95	2,460.15	11
	372.1 – 372.3	372.2	4,242.39	19
Total	Overall Average for 2002 = 371.77		21,868	100
2012	392.4 – 392.5	392.45	8,789.67	40
	392.6 – 392.7	392.65	6,587.18	30
	392.8 - 392.8	392.8	1,954.27	9
	392.9 – 393.0	392.95	3,488.97	16
	393.1 – 393.2	393.15	1,047.83	5
Total	Overall Average for 2012 = 392.80		21,867.92	100
2022	402.7 - 402.9	402.8	12,558.79	57
	403.0 – 403.1	403.05	4,039.02	18
	403.2 – 403.3	403.25	3,035.28	14
	403.4 – 403.6	403.5	1,804.11	8
	403.7 – 404.0	403.85	430.79	3
Total	Overall Average for 2022 = 403.29		21,867.99	100

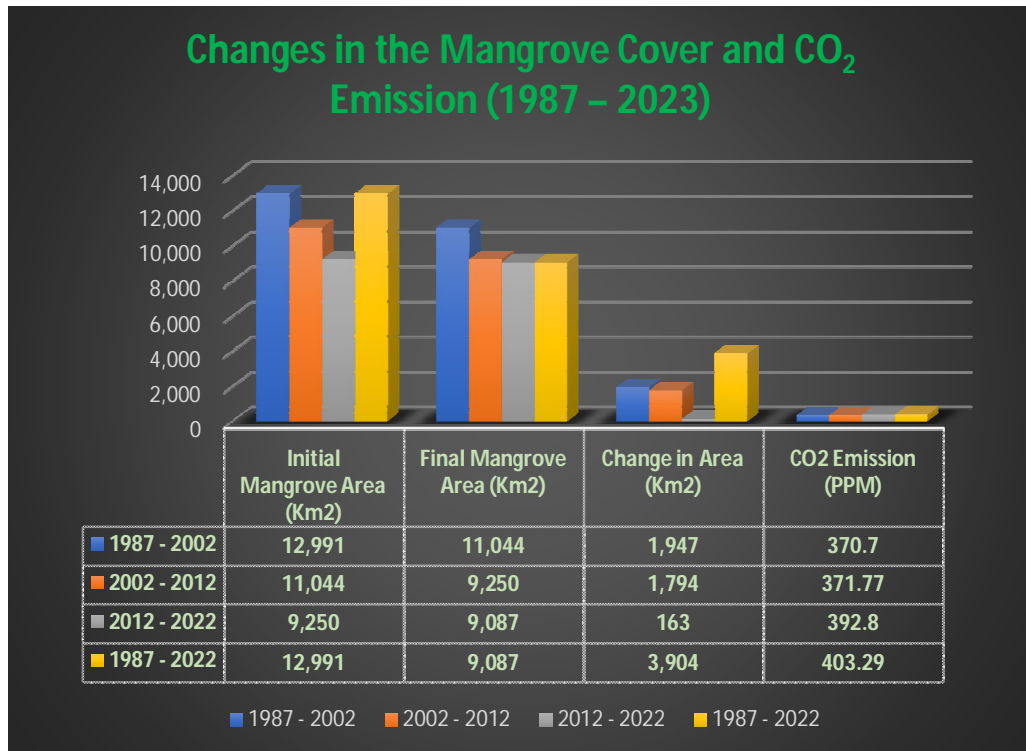


Figure 6. Chart Showing Initial Mangrove Area, Final Mangrove Area, Changes in the Mangrove Cover and CO₂ Emission (1987 – 2022)

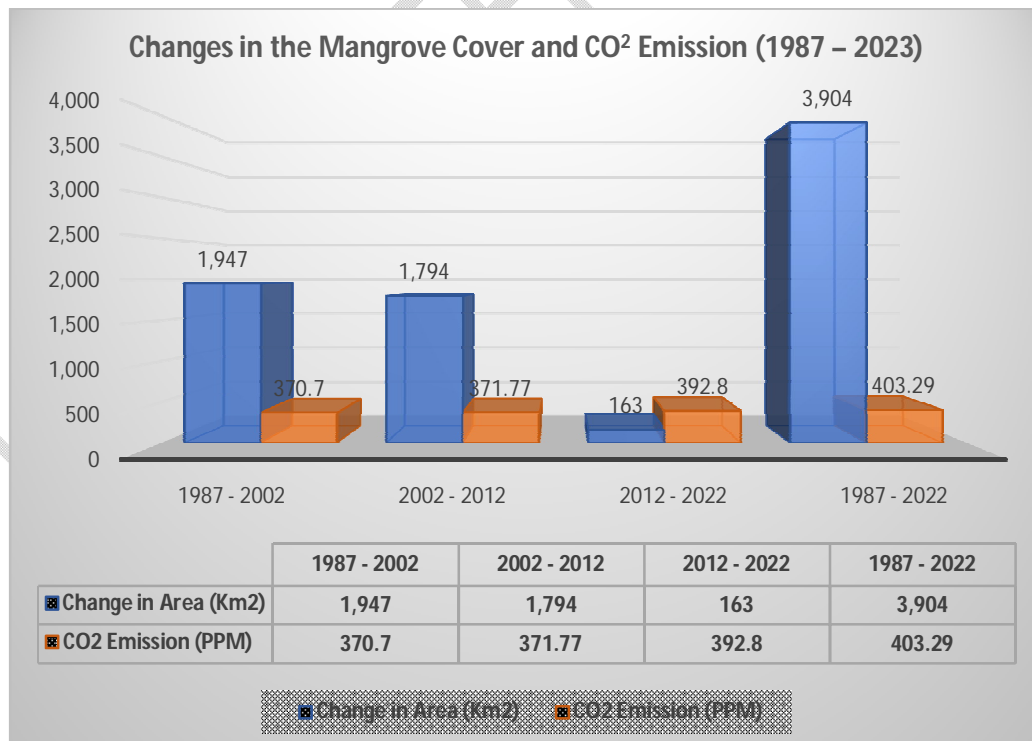


Figure 7. Chart Showing Changes in the Mangrove Cover and CO₂ Emission (1987– 2022)

Figures 6 and 7 outline changes in mangrove cover in the Niger Delta Region over various time periods (1987 – 2002, 2002 – 2012, 2012 - 2022) and associate these changes with CO₂ emissions expressed in parts per million (ppm). The data on the figure have been analyzed in order to understand the impacts of mangrove cover change on climate change under the following:

Time Periods, Mangrove Area Change and CO₂ Emissions in ppm

Data obtained (Figures 6 and 7) show that between 1987-2002, the mangroves within the study area decreased from 12,991 km² to 11,044 km², resulting in a loss of 1,947 km² and the CO₂ emissions associated with land use/land cover change within this period amounted to 370.70 ppm. Between 2002-2012, the mangroves within the study area further decreased from 11,044 km² to 9,250 km², resulting in a loss of 1,794 km², again, CO₂ emissions within this period, increased slightly to 371.77 ppm. From 2012 to 2022, the mangrove area decreased slightly again from 9,250 km² to 9,087 km², resulting in a much smaller loss of 163 km². Nevertheless, there was a significant rise in CO₂ emissions within this period from 371.77 ppm reaching 392.80 ppm. Overall, between 1987 and 2022, the total mangrove area decreased by 3,904 km², from 12,991 km² to 9,087 km² resulting in the total CO₂ emissions of 403.29 ppm over the period of 35 years.

Analysis of Impacts: Analysis of impacts for the emission of greenhouse gases resulting from the mangrove changes within the study area for the period of thirty-five (35) years is considered under correlation between mangrove loss and CO₂ emissions and their implication for climate change.

Correlation Between Mangrove Loss and CO₂ Emissions:

- a. **Significant Mangrove Loss (1987-2002 and 2002-2012):** During these periods, the most significant losses in mangrove area occurred, with 1,947 km² and 1,794 km² of mangroves lost, respectively. Correspondingly, CO₂ emissions were 370.70 ppm and 371.77 ppm respectively. The relatively steady and high levels of CO₂ emissions during these periods suggest that the destruction of mangroves led to significant CO₂ release and consequently contributes significantly to global warming. This is in consonance with the findings of Alongi *et al.*, (2014) that the destruction of about 0.7% of the tropical forest area globally has currently added 10% to global CO₂ release from tropical deforestations. This also collaborates the research by Arifantiet *al.*, (2022) that high mangrove deforestation rates especially in Kalimantan, Sumatra and Sulawesi resulted in high CO₂ emissions.
- b. **Reduced Mangrove Loss (2012-2022):** The reduction in mangrove loss during this period by only 163 km², is associated with a small increase in CO₂ emissions of 392.80 ppm. However, the emissions still rose, indicating that even minor losses in mangrove

cover can contribute to increased atmospheric CO₂, although to a lesser extent. However, the minor losses in mangrove areas recorded within this period and the resultant increased atmospheric CO₂, no matter how minimal, should not be taken for granted considering the report of (Richards *et al.*, 2020) that despite estimates of recent global mangrove loss slowing to 4.0% of global coverage between 1996 and 2016, that it has been estimated that > 300 million Mg of CO₂e were emitted as a result of mangrove deforestation between 2000 and 2012 (Hamilton and Friess, 2018). This position equally supports the findings of (Adame *et al.*, 2021) that between 2000 and 2016, 87% of mangrove loss in the West Coral triangle, where the vast majority of the world's mangroves organic carbon is stored, was due to agriculture/aquaculture land-use conversion.

C. Overall Impact (1987-2022): The study was able to show that the cumulative loss of 3,904 km² of the Niger Delta mangroves over the period of 35 years is associated with a total increase in CO₂ emissions of 403.29 ppm. This data suggests a strong relationship between the extent of mangrove loss and the rise in atmospheric CO₂ levels, reflecting the role of mangroves as carbon sinks. Consequently, it can be concluded that the depletion of the mangrove forest in the study area has contributed significantly to climate change. This conclusion is in consonance with the studies of (Barnes *et al.*, 2006) that emissions of carbon dioxide (CO₂) and methane (CH₄) by mangrove sediments are potential sources of greenhouse gas to the atmosphere and as such may contribute to global climate change.

Implications for Climate Change:

a. Accelerated CO₂ Concentration: The overall increase in emissions of CO₂ across the time periods indicates that the destruction of mangroves has contributed to the upsurge in the levels of carbon dioxide concentration in the atmosphere, thus aggravating the greenhouse effect and inducing global warming. This inference is in line with that of (Barnes *et al.*, 2006; Kristensen, 2007) respectively that mangroves can be an important source of CH₄ and N₂O to the atmosphere contributing to global climatic changes due to its warming potential (Chauhan *et al.*, 2015).

b. Potential for Mitigation: The decline in the rate of loss of mangroves from 2012 to 2022 means that if the rate of mangrove deforestation is reduced or stopped altogether, further increments in CO₂ emissions may be scaled down thus minimising the impacts or effect of global warming. Therefore, there is every likelihood that effective restoration and protection of the Niger Delta mangroves will result in a clear downward trend in the levels of CO₂ in the atmosphere. This position is in consonance with the publication of (Murdiyarso *et al.*, 2015; Taillardat *et al.*, 2018 and Cameron *et al.*, 2019) that mangrove conservation and restoration programs on a national scale have been identified as an

efficient means of offsetting GHG emissions. Although, according to (Kauffman *et al.*, 2017), the prevention of further forest loss, by far, outweighs gains from restoration.

- c. **Non-Linear Impact:** The data reveals that there is no direct relationship between change in the mangrove cover and level of CO₂ emissions. And that even little variations in the area of mangroves, mostly when their loss is negligible, is capable of causing substantial increment in the CO₂ highlighting how sensitive and responsive the atmospheric CO₂ level is to mangrove cover change or mangrove depletion. Nevertheless, the response of mangroves on elevated CO₂ varies between species, and depends on other environmental factors such as temperature, salinity, nutrient levels and the hydrologic regime (Field, 1995). Research on the effects of elevated CO₂ on mangroves are still lacking and poorly understood.
- d. **Impact of Mangrove Loss on CO₂ Emissions:** The data also showed a clear correlation between the loss of mangrove cover and increases in CO₂ emissions. As mangroves are destroyed, the carbon stored in their biomass and soils is released into the atmosphere, leading to higher CO₂ concentrations.
- e. **Temporal Variation:** The rate of mangrove loss decreased significantly in the most recent period (2012-2022), which could be due to increased conservation efforts or a natural slowdown in deforestation. However, despite this reduction in area loss, CO₂ emissions still increased significantly, suggesting that even smaller changes in mangrove cover can have a large impact on CO₂ levels.
- f. **Cumulative Impact:** The cumulative loss of mangrove covers over 35 years and the associated CO₂ emissions underline the critical role of mangroves in climate regulation. The large total reduction in mangrove area has likely contributed substantially to regional and potentially global increases in atmospheric CO₂, exacerbating climate change.

5. CONCLUSION

The study utilized Landsat data to assess the spatio-temporal dynamics of mangrove cover change in Niger Delta for the period 1987 – 2022 and the result reveals that between 1987 and 2022 (35years), the mangrove cover decreased by 63.7% (3,206.25 km²) at a rate of 100.20km² /yr or 1.99% yr⁻¹. The results of the study as discussed above illustrates a clear link between mangrove cover change and CO₂ emissions, highlighting the critical role mangroves play in climate change. The variation in mangrove cover change in the Niger Delta region has had a profound impact on the CO₂ emissions over the period from 1987 to 2022. Consequently, significant losses in mangrove cover have been closely associated with increased CO₂ emissions thus, reflecting the vital role these ecosystems play in carbon sequestration and temperature regulation. The recent slowdown in mangrove loss between

2012 and 2022 is promising, but the continued rise in concentration of CO₂ emissions in the atmosphere suggests that more aggressive conservation and restoration efforts are needed to mitigate climate change effectively. In conclusion, mangrove cover changes in the Niger Delta region have led to a consistent rise in increase in the concentration of CO₂ in the atmosphere, thus underscoring the importance of preserving these vital ecosystems to mitigate local climate impacts.

6. RECOMMENDATIONS

The findings of the study underscore the urgent need for concerted efforts to address both anthropogenic and natural drivers of mangrove depletion in the Niger Delta and as such, the following key policy recommendations are proposed for the sustainable management of mangroves in the Niger Delta region:

- i. Strengthening legal and policy frameworks by enacting comprehensive, stand-alone federal legislation for mangrove conservation and management, incorporating modern environmental principles and international best practices as well as revising and harmonizing outdated state and federal forestry laws to address the unique challenges of mangrove ecosystems.
- ii. Enhancing governance and institutional capacity by strengthening enforcement mechanisms and building institutional capacity to enforce mangrove protection laws, including monitoring illegal logging, oil pollution, and urban encroachment including ensuring community participation by involving local communities in decision-making and mangrove restoration projects to foster stewardship and compliance.
- iii. Restoration and rehabilitation of mangrove ecosystems by embarking on reforestation Programs like implementing large-scale mangrove reforestation projects using native species to restore degraded areas and controlling of invasive species by developing strategies to manage and reduce the spread of *Nypa fruticans* (Nipa palm), which displaces native mangroves.
- iv. Strengthening of pollution control measures focusing on oil spill management by enforcing stricter regulations on oil companies for pollution control and remediation, ensuring prompt cleanup of spills including monitoring and regulating coastal industries to minimize waste discharge into mangrove areas.
- v. Promoting sustainable livelihoods through alternative livelihood programs by providing training and support for sustainable income-generating activities, such as eco-tourism, aquaculture, and sustainable harvesting of mangrove resources.
- vi. Empowerment of women and youth focusing on involving vulnerable groups in conservation and livelihood initiatives to reduce dependence on destructive activities like charcoal production.
- vii. Integration of technological solutions using Geo-spatial tools to enhance the use of GIS and remote sensing for regular monitoring of mangrove cover and identifying areas under threat

- as well as establishing a comprehensive database to document mangrove health, biodiversity, and socioeconomic impacts, enabling informed decision-making.
- viii. Encouraging oil and gas companies to invest in mangrove restoration and education initiatives as part of their corporate social responsibility (CSR) activities.
 - ix. Fostering regional and international collaboration through: Cross-Border Cooperation (working with neighbouring countries to address transboundary issues, such as invasive species and pollution and Knowledge Exchange (collaborating with international experts and organizations to share best practices and technological advancements in mangrove management).

REFERENCES

1. Adame, M. F., Connolly, R. M., Turschwell, M. P., Lovelock, C. E., Fatoyinbo, T., Lagomasino, D., Goldberg, L. A., Holdorf, J., Friess, D. A., Sasmito, S. D., Sanderman, J., Sievers, M., Buelow, C., Kauffman, J. B., Bryan-Brown, D., and Brown, C. J., (2021). Future carbon emissions from global mangrove forest loss. *Global Change Biology*, 27: 2856–2866.
2. Agumagu, O., and Todd, M., (2015). Modelling the Climatic Variability in the Niger Delta Region: Influence of Climate Change on Hydrology. *Journal of Earth Science and Climate Change*, 6: 1–7.
3. Akpan, F. U., and Udo, E. E., (2017). Impact of agricultural activities on mangrove forests in the Niger Delta, Nigeria. *Nigerian Journal of Agriculture and Rural Development*, 8: 79-87.
4. Alongi, D. M., (2002). Present state and future of the world's mangrove forests. *Environmental Conservation*. 29:331–349.
5. Alongi, D. M., (2009). The energetics of mangrove forests. *Springer, New York*.
6. Alongi, D. M., (2012). Carbon sequestration in mangrove forests. *Carbon Management*, 3: 313–322.
7. Alongi, D.M., (2014). Carbon Cycling and Storage in Mangrove Forests. *Annual Reviews in Marine Science*, 6: 195–219.
8. Arifanti, V. B., Kauffman, J. B., Iلمان, M., Tosiani, A., and Novita, N., (2022). Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia. *Global Change Biology*, 28: 4523–4538.
9. Atwood, T. B., Connolly, R. M., Almahasheer, H., Carnell, P. E., Duarte, C. M., Lewis, C. J. E., Irigoien, X., Kelleway, J. J., Lavery, P. S., Macreadie, P. I., Serrano, O., Sanders, C. J., Santos, I., Steven, A. D. L., and Lovelock, C. E., (2017). Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change*, 7: 523–528.
10. Awosika, L.F., (1995). Impact of Global Climate Change and Sea Level Rise on Coastal Resources and Energy Development in Nigeria. In: Umolu, J.C., Ed., *Global Climate Change: Impact on Energy Development*, DAMTECH Nigeria Limited, Nigeria.

11. Ayanlade, A., (2012). Evaluating Environmental Change Impacts on Ecological Services in the Niger Delta of Nigeria. *Ife Research Publications in Geography*, 11: 11-125.
12. Barnes, L., and Lea-Greenwood, G., (2006). Fast Fashioning the Supply Chain: Shaping the Research Agenda. *Journal of Fashion Marketing and Management*, 10: 259-271.
13. Cameron, C., Hutley, L. B., and Friess, D. A., (2019). Estimating the full greenhouse gas emissions offset potential and profile between rehabilitating and established mangroves. *Science of the Total Environment*, 665: 419–431.
14. Canfield, D.E.,(2004). The evolution of the Earth surface sulfur reservoir. *American Journal of Science*,304:839– 61.
15. Chatting, M., Al-Maslamani, I., Walton, M., Skov, M. W., Kennedy, H., Husrevoglu, Y. S., and Le Vay, L., (2022). Future Mangrove Carbon Storage Under Climate Change and Deforestation. *Frontiers Marine Science*, 9:781876.
16. Chauhan, A., Saxena, D.C. and Singh, S., (2016). Physical, Textural, and Sensory Characteristics of Wheat and Amaranth Flour Blend Cookies. *Cogent Food and Agriculture*, 2: Article ID: 1125773.
17. Chen, X. R., *et al.* (2010). An investigation on health condition and sports behaviour of peasant workers in Pearl River Delta. *China Sport Science*, 30: 11-21.
18. Dangana, L. B., (1981). Ecological Dynamics and flood control in the Niger Delta. Presented in a Seminar on Flood and Erosion Control in the Niger Delta. Port Harcourt, 25–26 March 1981.
19. Donato, D. C., Kauffman, J. B., Murdiyarto, D., Kurnianto, S., Stidham, M., and Kanninen, M., (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4: 293–297.
20. Duke, N.C., (2016). Oil Spill Impacts on Mangroves: Recommendations for Operational Planning and Action Based on a Global Review, 109: 700–715.
21. Enaruvbe, G. O., and Atafo, O. P., (2014). Analysis of deforestation pattern in the Niger Delta region of Nigeria. *Journal of Land Use Science*, 11: 113–130.
22. Field, C. D., (1995). Impacts of Expected Climate Change on Mangroves. *Hydrobiologia* 295:75–81.
23. Goldenstein, C.S., Spearrin, R.M., Jeffries, J.B., and Hanson, R.K., (2017). Infrared laser-absorption sensing for combustion gases. *Progress in Energy and Combustion Science*, 60: 132–176.
24. Hamilton, S. E., and Friess, D. A., (2018). Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012. *Nature Climate Change*, 8: 240–244.
25. James, G.K., Adegoke, J.O., Osagie, S., Saba, E., Nwilo, P., and Akinyede, J., (2013). Social Valuation of Mangroves in the Niger Delta Region of Nigeria. *International Journal of Biodiversity Science, Ecosystem Services and Management*, 9: 311-323.
26. Kauffman, J. B., and Bhomia, R. K., (2017). Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: global and regional comparisons. *AppliedEcology*, 24: 518–527.

27. Kauffman, J. B., Heider, C., Norfolk, J., and Payton, F., (2014). Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. *Applied Ecology*,24: 518–527.
28. Komiyama, A., Ong, J. E., and Pongpam, S., (2008). Allometry, Biomass, and Productivity of Mangrove Forests: A Review. *Aquatic Botany*, 89: 128-137.
29. Kristensen, E.,(2007). Mangrove crabs as ecosystem engineers; with emphasis on sediment processes. *Journal of Sea Research*,59:30–43.
30. Lang'at, J. K. S., Kairo, J. G., Mencuccini, M., Bouillon, S., Skov, M. W., Waldron, S., et al. (2014). Rapid losses of surface elevation following tree girdling and cutting in tropical mangroves. *PLoS One* 9:e0118334.
31. Lovelock, C. E., and Reef, R., (2020). Variable Impacts of Climate Change on Blue Carbon. *One Earth*, 3: 195–211.
32. Lovelock, C. E., Russ, R. W., and Feller, I. C., (2011). CO₂ efflux from cleared mangrove peat. *PLoS One* 6:e21279.
33. Macreadie, P. I., Anton, A., Raven, J. A., Beaumont, N., Connolly, R. M., Friess, D. A., et al. (2019). The future of Blue Carbon science. *Nature Communications*, 10:3998.
34. Mayerhöfer, T.G., Mutschke, H., and Popp, J., (2016). Employing theories far beyond their limits—The case of the (Boguer-) Beer-Lambert law. *ChemPhysChem*, 17: 1948–1955.
35. Mcleod, E., Chmura., ouillon, S., Salm, R., jörk, M., uarte, C.M. et al. (2011). A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂. *Frontiers in Ecology and the Environment*, 9: 552–560.
36. Murdiyarto, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., and Donato, D. C., (2015). The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, 5: 1089–1092.
37. Murray, B. C., Pendleton, L., Jenkins, W. A., and Sifleet, S. J. G., (2011). Green payments for blue carbon: Economic incentives for protecting threatened coastal habitats. Nicholas Institute Report.
38. Nellemann, C., and Corcoran, E., (2009). Blue carbon: The role of healthy oceans in binding carbon: A rapid response assessment. UNEP/ Earthprint.
39. Nelson, P.N., and Oades, J.M., (1998). Organic Matter, Sodicity and Soil Structure, In: Sumner, M.E. and Naidu, R., Eds., *Sodic Soils: Distribution, Properties, Management and Environmental Consequences*, Oxford University Press, New York, 51-75.
40. Nguyen, H.T., Do, V.N., Nguyen, T.M., Le, X.T., Phan, H.A., Nguyen, H.T., Nguyen, K.C., and Le, H.G., (2000). Valuation of the Mangrove Ecosystem in Can Gio Mangrove Biosphere Reserve; Vietnam, MAB/UNESCO; The Vietnam MAB National Committee: Hanoi, Vietnam, 2000.
41. Nwilo, P.C., and Badejo, O.T., (2006) Impacts and Management of oil Spill Pollution along the Nigerian Coastal Areas. Administering Marine Spaces: International Issues. A Publication of FIG Commission 4 & 7 Working Group 4.3.

42. Ohwo, O., (2015). Public Perception of Climate Change in Yenagoa, Bayelsa State, Nigeria, *Geography Journal*, 208154: 1-10.
43. Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., and Jenkins, W.A., (2012). Estimating global “blue carbon” emissions from conversion and degradation of vegetated coastal ecosystems. *PloS One*, 7: e43542.
44. Richards, D. R., Thompson, B. S., and Wijedasa, L, (2020). Quantifying net loss of global mangrove carbon stocks from 20 years of land cover change. *Nature Communications*, 11:4260.
45. Sanderman, J., Hengl, T., Fiske, G., Solvik, K., Adame, M. F., Benson, L., Bukoski, J. J., Carnell, P., Cifuentes-Jara, M., and Donato, D., (2018). A global map of mangrove forest soil carbon at 30 m spatial resolution. *Environmental Research Letters*, 13: 055002.
46. Stockmann, U., Adams, M. A., Crawford, J. W., Field, D. J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A. B., Courcelles, V. D. R. D., Singh, K., Wheeler, I., Abbott, L., Angers, D. A., Baldock, J., Bird, M., Brookes, P. C., Chenu, C., Jastrow, J. D., Lal, R., Lehmann, J., O'Donnell, A. G., Parton, W. J., Whitehead, D., and Zimmermann, M. (2013). The Knowns, Known Unknowns and Unknowns of Sequestration of Soil Organic Carbon. *Agriculture, Ecosystems & Environment*, 164: 80-99.
47. Taillardat, P., Friess, D. A., and Lupascu, M., (2018). Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale. *Biology Letters*, 14: 20180251.
48. Duarte, C.M., Middelburg, J.J., and Caraco, N., (2005). Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences*, 2: 1–8.
49. Duke, N.C., Meynecke, J.-O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Cannicci, S., Diele, K., Ewel, K. C., Field, C. D., Koedam, N., Lee, S. Y., Marchand, C., Nordhaus, I., and Dahdouh-Guebas, F., (2007). A world without mangroves? *Science*, 317, 41–42.
50. Uyigue, E., and Agho, M., (2007). Coping with Climate Change and Environmental Degradation in the Niger Delta of Southern Nigeria. Community Research and Development Centre Nigeria (CREDC).
51. Wang, P., Numbere, A., O., and Camilo, G. R., (2016). Long-Term Changes in Mangrove Landscape of the Niger River Delta, Nigeria. *American Journal of Environmental Sciences*, 12: 248-259.
52. Windham-Myers, L., Crooks, S. and Troxler, T.G. (eds.). (2019). A Blue Carbon Primer: The State of Coastal Wetland Carbon Science, Practice and Policy. *Boca Raton, U.S.A.: CRC Press*.
53. Yu, O., and Chmura, G. L., (2009). Soil carbon may be maintained under grazing in a St Lawrence Estuary tidal marsh. *Environmental Conservation*, 36: 312–320.