Impacts of Mangrove Loss on Greenhouse Gas Emissions in the Niger Delta, 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. 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.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 CO_2 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. The data obtained revealed mangrove reduction from 12,991 km^2 in 1987 to 9,089km^2 in 2022 resulting in the loss of 3,904.00 km^2 of mangrove forest. The reduction resulted in increased CO_2 emissions from 370.70 ppm to 403.29 ppm between 1987 and 2022. These results illustrate a clear link between mangrove cover change and CO_2 emissions, highlighting the critical role mangroves play in regulating climate change. The study was able to show that significant losses in mangrove cover have been closely associated with increased CO_2 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,* Urbanization

1. INTRODUCTION

Mangroves are characterized by their high productivity (Komiyama *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 CO_2, 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 CO_2" (Pendleton *et al*., 2012; Windham-Myers *et al*., 2019).

"Emissions of carbon dioxide (CO_2) and methane (CH_4) 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 $CO_{2"}$ (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 CO_2 because CH_4 has about 20 times greater global warming potential than CO_2. CH_4 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).

Mangroves within the Niger Delta community proffer an avenue to address and promote life on land in line with the sustainable development goals (SDG). They aid in offering protection towards land degradation, thwarting the effects of extreme weather including absorption of emissions. Mangroves possess highly established root systems that also promote sediment deposits, modulate water flow, filtration of essential cations, etc. Periodic assessment of the mangrove ecosystem also serves to protect the vast diversity of flora and fauna, thus meeting the call to action for the protection, restoration and promotion of sustainable land practices. Within the Niger Delta, mangroves can be seen as a bridge between life on land and climate change by virtue of its carbon sequestration ability. Also, mangroves in the Niger Delta protect such coastal communities from raising sea levels as well as the deleterious effects of storms, whilst sustaining the associated cities and communities, thereby addressing SDGs 1, 2, 6, 11, 15 and 16 (Bajaj *et al.,* 2024).

"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 CO_2e 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 → 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'at*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, Chatting*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 CO_2e 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 *etal*., (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 CO_2) 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.

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 CO_2 emissions and land surface temperature (LST) of the study area.

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 km^2 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 km^2 of the Niger Delta land; stagnant swamps cover approximately 8600 km^2, while the mangrove swamp with about 1900 km^2 is considered Africa's largest (Uyigue and Agho, 2007).

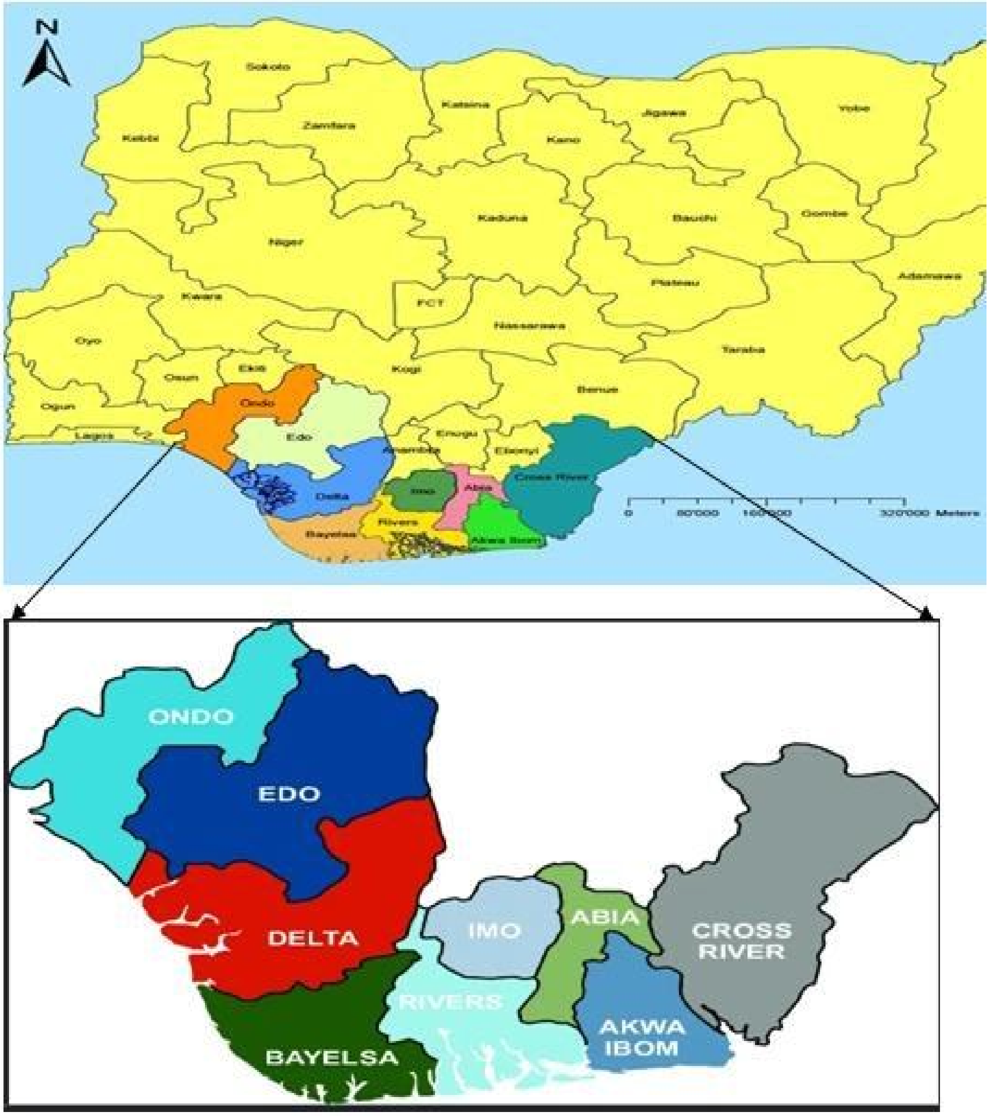


Figure 1. Map of Nigeria Showing Niger Delta Region

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 (%) = New Value – Old Value/Old Value x 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 = New Value (km^2) – Old Value (km^2).
d. Annual Rate of Change = Total Change/Old Value/No. of Years x 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:

$$T = P(\lambda)/ P0(\lambda) = 10^{-\varepsilon(\lambda)\cdot l\cdot c}$$

Where P denotes the transmitted light radiant power of the cell,

P0 denotes the initial light radiant power,

T denotes the transmittance,

ε(λ) cm^2/mol denotes the molar absorption coefficient at wavelength, λ,

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

The transmittance (T) is the ratio of the initial light radiant power (P0) 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

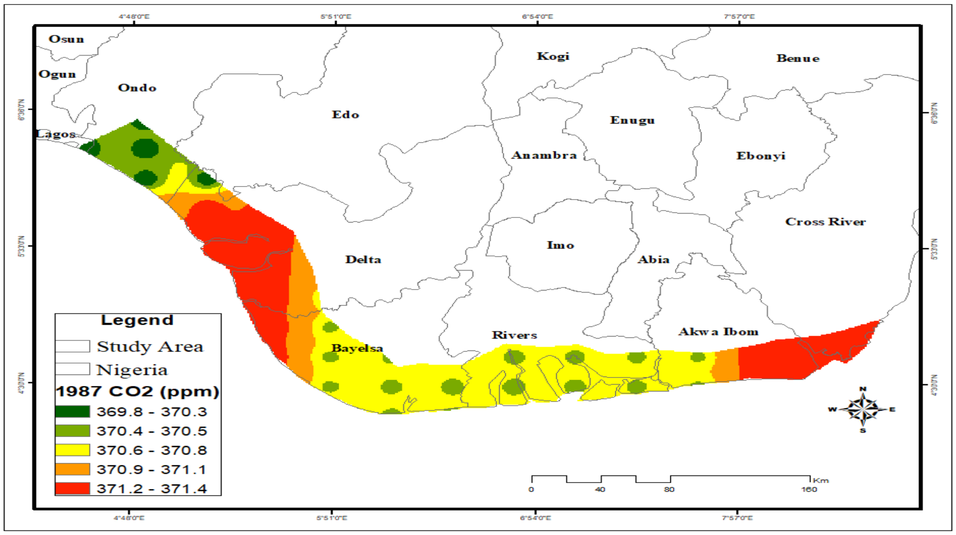


Figure 2. Greenhouse Gasses Emission Map (1987)

Figure 2 shows the concentration of CO_2 in the atmosphere within the study area in the year 1987. As at 1987, the lowest concentration of CO_2 was 369.8 ppm while the highest concentration of CO_2 was about 371.4 ppm distributed across the study area.

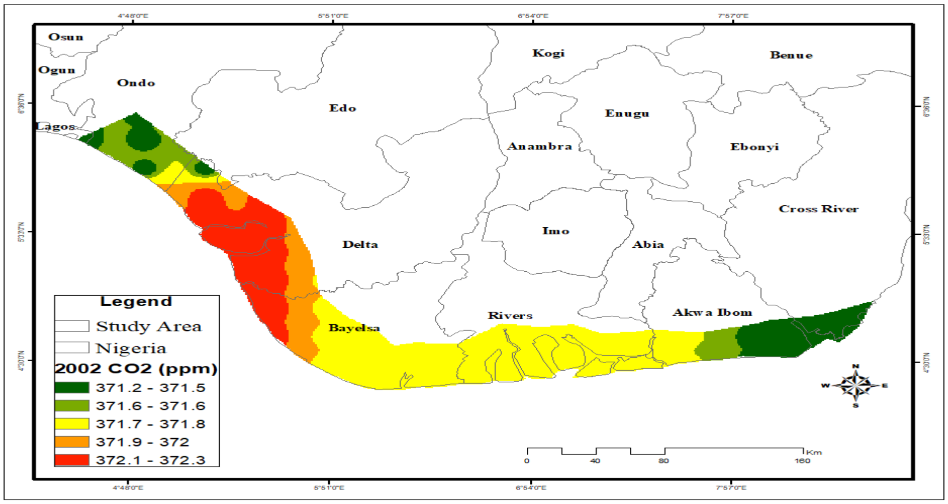


Figure 3. Greenhouse Gasses Emission Map (2002)

Year 2002 showed increase in the concentration of CO_2 as compared to the year 1987 with the minimum concentration of about 371.2 ppm while the maximum concentration was about 372.3 ppm.

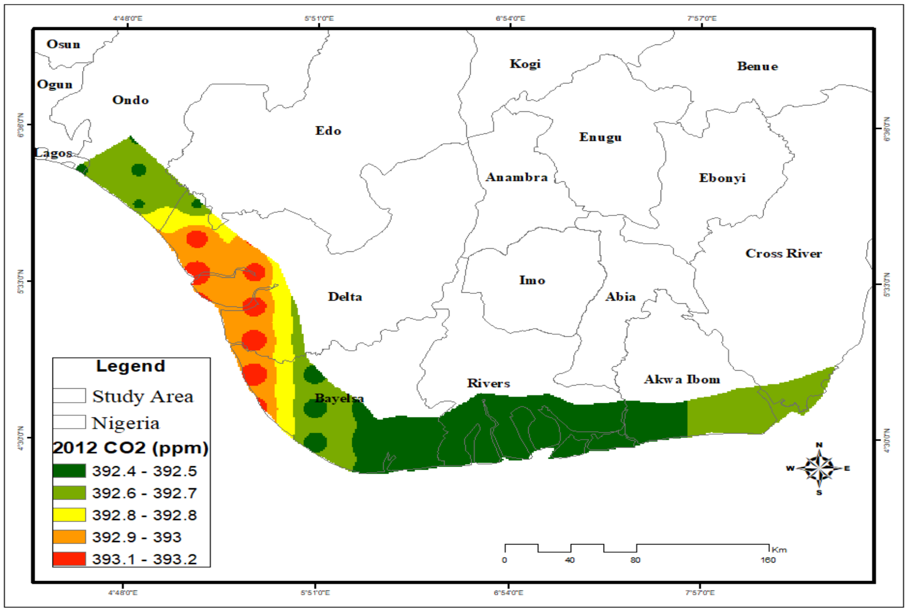


Figure 4.

Greenhouse Gasses Emission Map (2012)

In the year 2012, the concentration of CO_2 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.

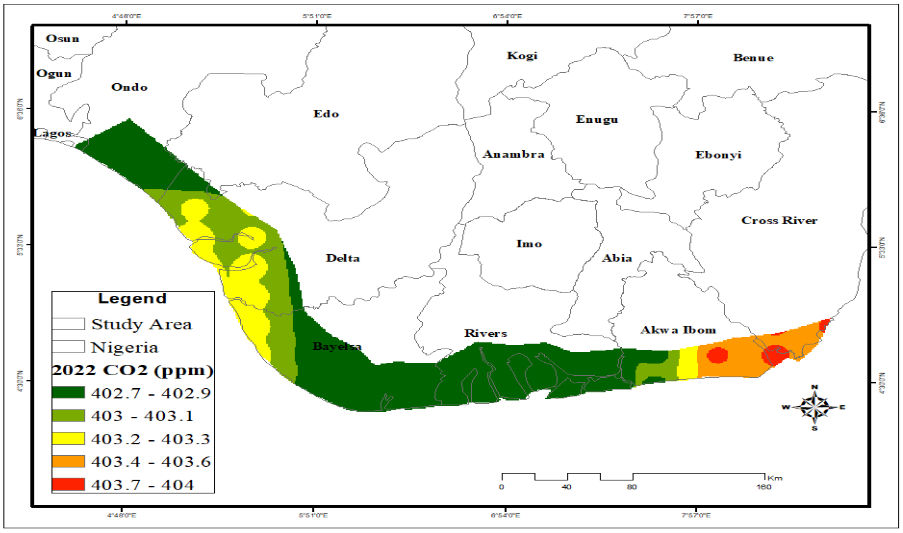


Figure 5.

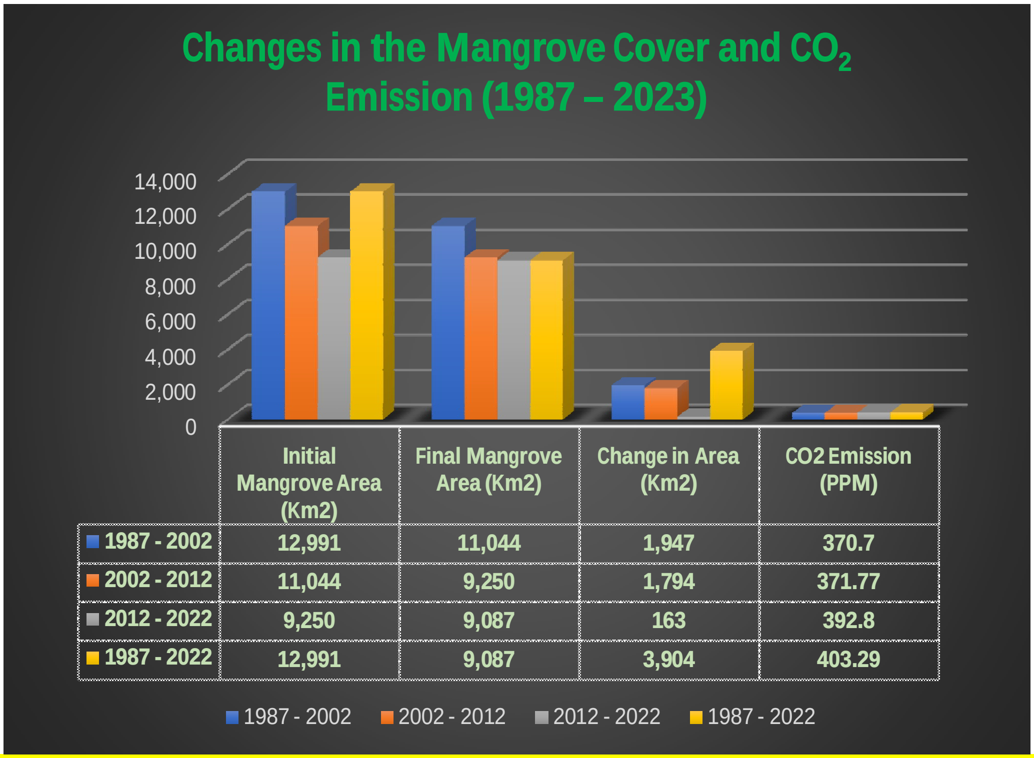
Greenhouse Gasses Emission Map (2022)

A further increase in the concentration of the atmospheric CO_2 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 (CO_2) in the atmosphere is typically measured in parts per million (ppm). This unit indicates the number of CO_2 molecules per million molecules of air. For example, if the CO_2 concentration is 420 ppm, it means there are 420 molecules of CO_2 in every million molecules of air.

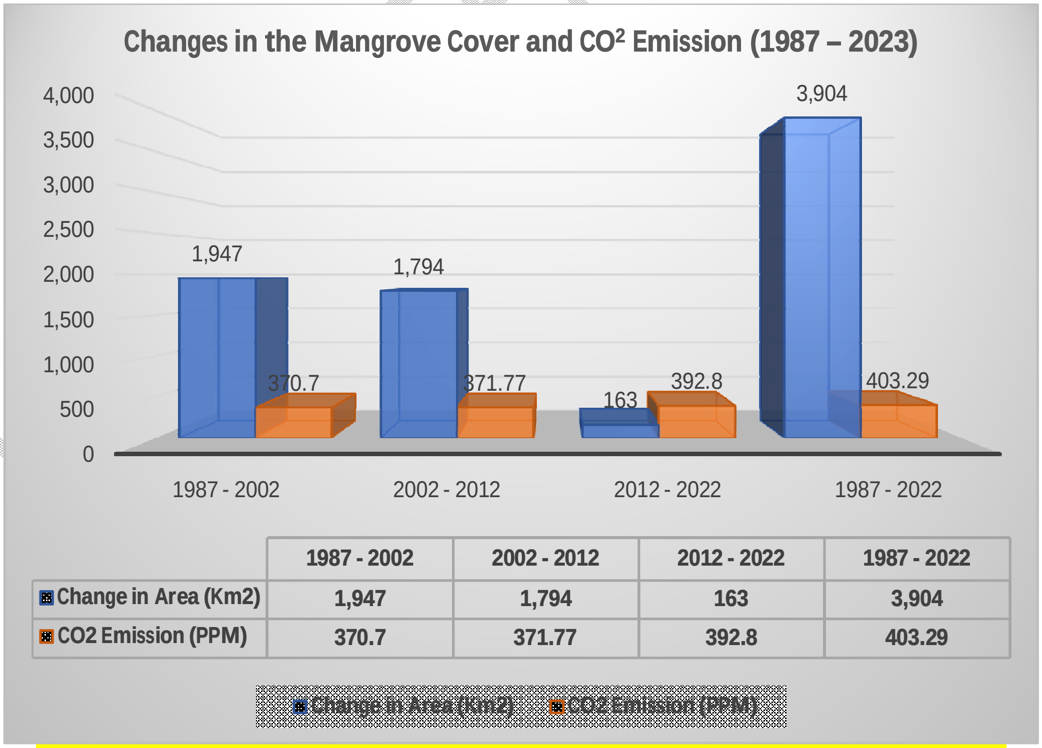
Table 2. CO_2 Emissions from Change in Mangrove Cover of Study Area (1987 – 2022)

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**



	Initial Mangrove Area (Km2)	Final Mangrove Area (Km2)	Change in Area (Km2)	CO2 Emission (PPM)
1987 - 2002	12,991	11,044	1,947	370.7
2002 - 2012	11,044	9,250	1,794	371.77
2012 - 2022	9,250	9,087	163	392.8
1987 - 2022	12,991	9,087	3,904	403.29

Figure 6. Chart of Initial Mangrove Area, Finial Mangrove Area, Changes in the Mangrove Cover and CO^2 Emission (1987 – 2022)



	1987 - 2002	2002 - 2012	2012 - 2022	1987 - 2022
Change in Area (Km2)	1,947	1,794	163	3,904
CO2 Emission (PPM)	370.7	371.77	392.8	403.29

Figure 7. Chart ofChanges in the Mangrove Cover and CO$_2$ Emission (1987– 2022)

Figures6 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 CO_2 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 CO_2 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 CO_2 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 km^2 to 9,250 km², resulting in a loss of 1,794 km², again, CO_2 emissions within this period, increased slightly to 371.77 ppm. From 2012 to 2022, the mangrove area decreased slightly again from 9,250 km^2 to 9,087 km², resulting in a much smaller loss of 163 km². Nevertheless, there was a significant rise in CO_2 emissions within this period from 371.77ppm 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 CO_2 emissions of 403.29 ppm over the period of 35years.

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 CO_2 emissions and their implication for climate change.

Correlation Between Mangrove Loss and CO_2 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, CO_2 emissions were 370.70 ppm and 371.77 ppm respectively. The relatively steady and high levels of CO_2 emissions during these periods suggest that the destruction of mangroves led to significant CO_2 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 CO_2 release from tropical deforestations. This also collaborate the research by Arifanti*et al.,* (2022) that high mangrove deforestation rates especially in Kalimantan, Sumatra and Sulawesi resulted in high CO_2 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 CO_2 emissions of 392.80 ppm. However, the emissions still rose, indicating that even minor losses in mangrove cover can contribute to increased atmospheric CO_2, although to a lesser extent. However, the minor losses in mangrove areas recorded within this period and the resultant increased atmospheric CO_2, 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 CO_2e 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):**Thewas able to show that the cumulative loss of 3,904 km^2 of the Niger Delta mangroves over the period of 35 years is associated with a total increase in CO_2 emissions of 403.29 ppm. This data suggests a strong relationship between the extent of mangrove loss and the rise in atmospheric CO_2 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 (CO_2) and methane (CH_4) 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 CO_2 Concentration:** The overall increase in emissions of CO_2 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 CH_4 and N_2O 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 CO_2 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 CO_2 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 CO_2 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 CO_2 highlighting how sensitive and responsive the atmospheric CO_2 level is to mangrove cover change or mangrove depletion. Nevertheless, the response of mangroves on elevated CO_2 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 CO_2 on mangroves are still lacking and poorly understood.

d. **Impact of Mangrove Loss on CO_2 Emissions:** The data also showed a clear correlation between the loss of mangrove cover and increases in CO_2 emissions. As mangroves are destroyed, the carbon stored in their biomass and soils is released into the atmosphere, leading to higher CO_2 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, CO_2 emissions still increased significantly, suggesting that even smaller changes in mangrove cover can have a large impact on CO_2 levels.

f. **Cumulative Impact:** The cumulative loss of mangrove covers over 35 years and the associated CO_2 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 CO_2, 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 km^2) at a rate of 100.20km^2 /yr or 1.99% yr $-^1$. The results of the study as discussed above illustrates a clear link between mangrove cover change and CO_2 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 CO_2 emissions over the period from 1987 to 2022. Consequently, significant losses in mangrove cover have been closely associated with increased CO_2 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 CO_2 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 CO_2 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 mechanismsand 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).

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1.

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3.

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