Impacts of Mangrove Cover Changes on the Land Surface Temperature in the Niger Delta Region of Nigeria

ABSTRACT

Nigeria has the third largest mangrove forest in the world, the largest in Africa with approximately 80% of its mangrove vegetation located within the Niger Delta region of the Country. Unfortunately, rapid urbanization has resulted in widespread mangrove loss which could lead to increased surface land temperatures (LST) culminating in the threat to the integrity of this ecosystem.

Aim: The study assessed the impacts of mangrove cover changes on climate change in the Niger Delta Region of Nigeria with the aim of articulating sustainable mangrove management practices.

Place and Duration of Study: Mangrove covers from 1987 to 2022 in the study area which includes nine states of Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo, Rivers, and Abia, and encompasses significant mangrove forests.

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 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. LST was derived from the geometrically corrected Landsat 5 and Landsat 8.

Result: The data obtained revealed mangrove reduction from 12,991 km^2 in 1987 to 9,089km^2 in 2022 resulting in the increased LST from 26.01°C to 28.07°C respectively within the pace of thirty-five (35) years. These results illustrate a clear link between mangrove cover change and variation in the LST, highlighting the critical role mangroves play in regulating climate change.

Conclusion: There are significant losses in mangrove cover have been closely associated with increased LST, 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, land surface temperature, climate change.

1. INTRODUCTION

Land surface temperature (LST) is an important factor in global change studies, in estimating radiation budgets in heat balance studies and as a control for climate models. The knowledge of surface temperature is important to a range of issues and themes in earth sciences central to urban climatology, global environmental change, and human-environment interactions (Li *et al.,* 2023). The climate in and around cities and other built-up areas is altered due to changes in LU/LC and anthropogenic activities of urbanization (Zhou *et al.,* 2018). The most imperative problem in urban areas is increasing surface temperature due to alteration and conversion of vegetated surfaces to impervious surfaces (Zhou *et al.,* 2018). These changes affect the atmospheric solar concentration, radiant heat, dehydration rates, wind velocity, heat conduction, etc in addition to extreme changes to the troposphere in most cities (NourEldeen *et al.,* 2020).

Land surface temperature can provide important information about the surface physical properties and climate which plays a role in many environmental processes (Chen *et al.,* 2022). A number of research efforts into this subject has ascertained that by calculating the air temperature via surface-based observation stations, it is possible to determine the relative warmth of any city globally. Some studies used measurements of temperature using temperature sensors mounted on car, along various routes (Fonseka *et al.,* 2019). However this approach is neither cost effective nor efficient and in most cases would lead to false positive or false negative geometric calculation. A cheaper and rapid approach would be that of remote sensing. Land surface temperature is sensitive to vegetation and soil moisture; hence it can be used to detect land use/land cover changes, e.g. tendencies towards urbanization, desertification etc. Various studies have been carried out to investigate LST using the vegetation abundance and how it affects atmospheric attenuation, gradual release of gases to the ozone layer as well as the downward long-wave radiation (DLWR) on the earth surface (Pierangelo *et al.,* 2004; (Feng *et al.,* 2019). The urban environments is plagued with an ever increasing land surface temperature as a result of the near total destruction of vegetative land cover and its replacement with concrete walkways and other artificial surfaces (Mallick *et al.,* 2008), transformation of vegetated and wetland into agricultural land or bare waste land (Arsiso *et al.,* 2023). These changes affect the degree of absorption of solar radiation, reflective power, surface temperature, evaporation rates, transmission of heat to the soil, storage of heat, wind turbulence and can severely change the natural state of tropospheric conditions over the cities (Mallick *et al.,* 2008), deter the energy/water flux (Oke, 1987) and also temper with several ecological processes (Feng *et al.,* 2019). In attempt to illuminate the relationship between rapid urbanization and LST, Ogashawara and Brum Bastos (2012) examined the link between aquatic environs and floral to LST within the metropolitan areas of Brazil. Their results suggested that the developed urban settlements generated a rising surface temperature alongside in contrast to a lower LST in control areas with dense floral cover and the country's coastal/rural areas. Pal and Ziaul (2017), explained urban heat island effect by three factors: the effects of energy transformation in cities; the decrease of evapotranspiration; and, the production of anthropogenic energy. He also, depicted three types of UHIs: Canopy Layer Heat Island (CLHI); Boundary Layer Heat Island (BLHI); and, Surface Heat Island (SHI). Fabrizi et al. (2010) concluded that SHI was responsible for the increased temperatures observed on the urban surface while a combination of the BLHI and CLHI were the main culprit of the warm urban atmosphere.

The scientific justification that once mangroves are lost, the cooling benefits they provide may take time to regenerate is supported by ecological research that highlights the key roles mangroves play in temperature regulation and their slow recovery process after disturbance. Mangroves regulate local microclimates by providing shade and through the process of evapotranspiration (Wan, 2014). This process releases moisture into the atmosphere, which cools the surrounding environment. When mangroves are lost, the immediate removal of this cooling function results in increased surface temperatures (Wan, 2014). The recovery of this cooling benefit takes time as new mangrove trees need years to develop their full canopy structure and mature root systems. Accordingly, Wan, (2014) demonstrated the role of evapotranspiration in moderating local climates in mangrove ecosystems. In degraded or deforested mangrove areas, it was discovered that there is a measurable increase in land surface temperature due to the absence of shade and transpiration from vegetation Soil Heat Absorption and Carbon Storage. Kauffman *et al.,* (2014) also noted that mangrove ecosystems can sequester large amounts of carbon, and when they are degraded, the release of carbon and the exposure of previously shaded soils can lead to significant increases in surface temperature. When mangroves are cleared, the exposed soils are prone to absorbing more solar radiation, resulting in an increase in land surface temperature. Mangrove soils are rich in organic matter and water content, both of which help to maintain cooler surface temperatures. Once disturbed, these soils tend to dry out and lose their heat-buffering capacity. Regenerating these soil conditions, especially the organic content, takes years, during which time the land remains hotter.

Mangrove trees are known to grow slowly, especially under harsh conditions such as high salinity, nutrient-poor soils, or after disturbances like deforestation (Bosire *et al.,* 2008). Studies have shown that it can take several decades for mangroves to fully recover and regenerate their ecological functions, including temperature regulation. The cooling benefits that result from a mature mangrove forest canopy take time to return after restoration or natural regeneration begins. Bosire *et al.,* (2008) provided evidence that the full recovery of ecological functions in restored mangroves, including temperature regulation, can take decades depending on the extent of degradation, local environmental conditions, and management practices. Moreso, mangroves are among the most carbon-dense ecosystems on the planet, storing large amounts of carbon in their biomass and soils (Donato *et al.,* 2011). When mangroves are cleared, this carbon is released into the atmosphere, contributing to the greenhouse effect and global warming (Donato *et al.,* 2011). The cooling benefits of carbon sequestration provided by mature mangroves take time to recover because the newly planted or regenerating mangroves take years to accumulate carbon at the same levels as mature forests (Donato *et al.,* 2011). Walters *et al.,* (2008) reviewed the recovery of ecosystem services following mangrove deforestation and found out that cooling effects of mangroves are part of a broader suite of ecosystem services, including biodiversity support, carbon storage, and water regulation. When mangroves are destroyed, these services are lost, and while restoration efforts can be successful, there is a lag time before these benefits are fully restored. This delay is due to the time needed for tree growth, soil stabilization, and the re-establishment of hydrological and microclimate processes that mangroves support (Walters *et al.,* 2008).

Across Asia, several metropolitan cities were monitored for LST and mangrove depletion by several research teams (Grover and Singh, 2015). Unfortunately no such works have been carried out for the small towns especially those that have also started nucleating heating problem. Monitoring of those can help to provide early step for adopting suitable policies for either overcoming or minimizing the problems. Keeping this concern in mind, the present work is based on highly populated and rapidly growing Niger Delta Region of Nigeria and the changes in the mangroves within its constituent States of Akwa Ibom, Bayelsa, Cross River, Delta, Ondo and Rivers (Oke, 1987). Moreover, the average meteorological density (likely referring to atmospheric density or air density) in the Niger Delta region of Nigeria, which is a plain and coastal area, is influenced by factors like temperature, humidity, and altitude. In general, the Niger Delta is a tropical region, with temperatures ranging from 24°C to 32°C and higher temperatures lead to lower air density (Oke, 1987). The region also has high humidity levels, which also reduces air density. Being a low-lying plain, the Niger Delta is near sea level, so its altitude doesn't significantly reduce air density. Therefore, using the International Standard Atmosphere (ISA) model as a baseline, the air density at sea level under standard conditions (15°C and 1013.25 hPa) is around 1.225 kg/m³ (Oke, 1987). However, in tropical regions like the Niger Delta, with higher temperatures and humidity, the density would be somewhat lower and a rough estimate for the Niger Delta's air density, given the local temperature and humidity, might be around 1.15 to 1.20 kg/m³ (Oke, 1987).

2. Study area, data type, acquisition and analysis

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 which spans several villages and a gamut of communities (Akpan *et al*., 2017). In total, there are 13,329 settlements in the Niger Delta Region (Enaruvbe and Atafo, 2014). Data from the country’s 1991 census revealed that the inhabitants of the Niger Delta region increased by 30 million which represented a 2.9% rise in 13 years. 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 north eastern 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 Niger Delta region exhibited an average monthly temperature ranging 25^{o}C to 29^{o}C coupled to a 2000mm to 4000mm precipitation range annually and a relative humidity index above 70%, all of which spans its dry and rainy seasons (Nwilo and Badejo, 2006). Its dry season commences between November and February with an intermission of harmattan during the months of December and February, the lattar triggered by a dense-northern flow of air that sweeps across the continent (Ohwo, 2015). Its evolutionary landforms comprises barrier lagoons, mud and strand coasts (Agumagu, 2015). Furthermore, aquatic distribution of creeks, estuaries and rivers measures 2370 km^2 of the land mass while its swamp environment is estimated at 8600 km^2 with its mangrove swamp cover spans approximately 1900 km^2 (Uyigue and Agho, 2007).

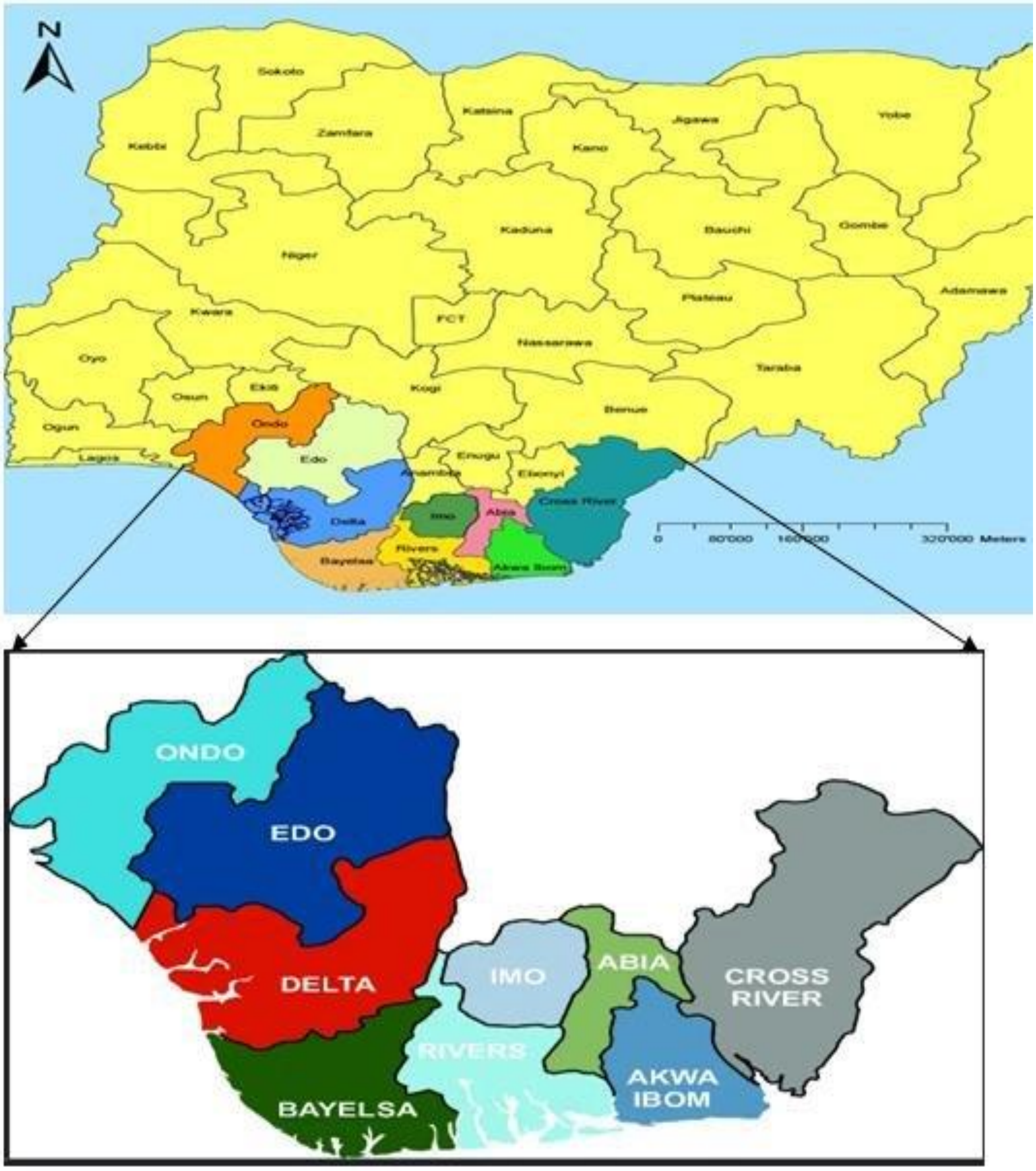


Figure 1. Map of Nigeria Showing Niger Delta Region

3. Methodology

The details of the procedure have been reported (Useh *et al.,* 2025). Satellite imagery to capture temperature changes was employed for the study area which covered all mangrove areas within Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo and Ondo states between 1987 and 2022. Other source data utilized included climate data, carbon sequestration and socioeconomic assessment. Data generation depicting land use and mangrove cover was obtained from Landsat Thematic Mapper (TM) imaging and verified with ArcGIS 10.8 to Universal Transverse Mercator (Useh *et al.,* 2025). Image processing, classification and change detection analysis were done following previously used procedures (Useh *et al.,* 2025).

Formulas:

Landsat Satellite image (LANDSAT 5 TM, 1990) and (LANDSAT 8 OLI, 2014) images of 1987, 2002, 2012 and 2022 in the Nigeria Niger Delta Biosphere Reserve were used for the land use/land cover classification and the thermal bands of the corresponding Landsat was used to obtain the Land surface temperature. Land use land cover maps of the study area from 1997 to 2022 were generated by supervised classification and maximum likelihood method was used for this classification. The pixel sample ware selected from various spectral classes and run the data using maximum likelihood method. Final groping of similar pixels was done on the basis of sampled pixels for various land use/land cover classes. The generalized images were reclassified to reduce classification error and improve the accuracy of the classification.

Surface temperature was derived from geometrically corrected Landsat 5 TM (band 6) and Landsat 8 TIRS (band 10 and 11). Spectral radiance model was used to retrieve surface temperature from Landsat 5 TM and split window method was used to retrieve surface temperature from LANDSAT 8 TIRS. A three-step process was followed to derive surface temperature from Landsat TM 5 Image. Spectral radiance was calculated using following equation:

$$\mathrm{L = LMIN + (LMAX - LMIN) \times DN/255} \ldots\ldots\ldots \text{(eqn 1)}$$

where L = Spectral Radiance, LMIN = 1.238, LMAX = 15.600, DN = Digital Number.

Spectral Radiance (L) to Temperature in Kelvin may be expressed as:

$$T_B = K_2 / ln(K_1 L + 1) \ldots\ldots\ldots \text{(eqn 2)}$$

where K_1 = Calibration Constant 1 (607.76), K_2 = Calibration Constant 1 (1260.56), T_B = Surface Temperature.

Surface temperature from Landsat 8 TIRS was derived using band 10 and 11 following the split-window method first proposed by Mc Millin in 1975. The algorithm is:

$$LST = TB10 + C1(TB10 - TB11) + C2(TB10 - TB11)2 + C0 + (C3 + C4W)\ (1-\varepsilon) + (C5 + C6W)\ \Delta\varepsilon \ldots\ldots \text{(eqn 3)}$$

Where LST = Land surface temperature, C0–C6 = Split-window coefficient values, TB_{10} and TB_{11} = Brightness temperature of band 10 and band 11, ε = M band 10 and band 11, ε = Mean LSE of TIR bands, W = Atmospheric water vapor content, Δε = Difference in LSE.

The value of Top Atmospheric Spectral Radiance (TOAr) is determined by converting original DNs and TIRS into atmospheric radiance. The original Digital Numbers (DN) of Landsat 8 TIR is converted into radiance based on the methods provided by Chander and Markham (2003)

$$TOAr = ML \times DN + AL \text{..................................} \quad \text{(eqn 4)}$$

where A_L = Radiance add, M_L = Radiance multiplier, DN = Digital number.

The Brightness temperature (TB) for both TIR bands was calculated by adapting the following formula:

$$TB = K2Ln[(K1TOAr)+1] \text{....................................} \quad \text{(eqn 5)}$$

where K1 and K2 = Thermal constant for TIR bands, TB = Brightness temperature, TOAr = Atmospheric spectral radiance.

4. RESULTS AND DISCUSSION

This section illustrates the spatial distribution of Land Surface Temperature in the year 1987, 2002, 2012 and 2022 and also assesses the dynamics across the 35 years.

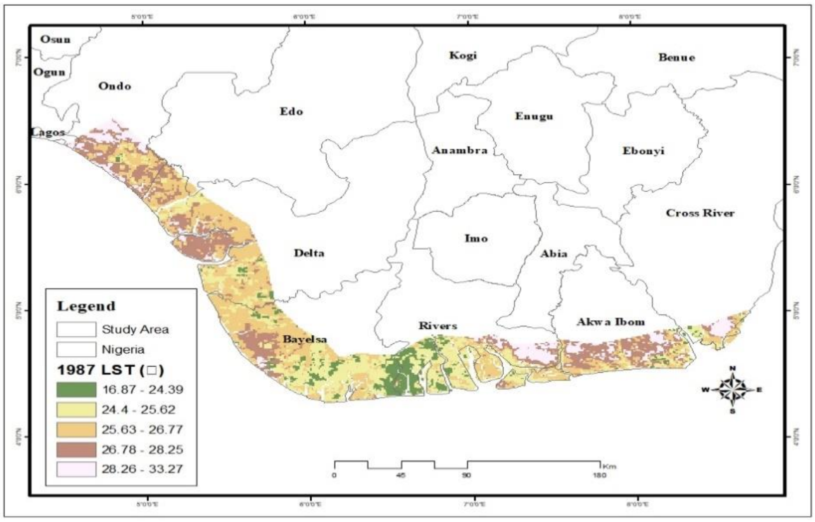


Figure 2. Map showing the spatial Pattern of LST across Niger Delta Region in (1987)

Figure 2 above shows the spatial distribution of Land Surface Temperature in the year 1987. As at 1987, the lowest Land Surface temperature (LST) was 16.87 ºC while the highest LST was about 33.27ºC distributed across the study area.

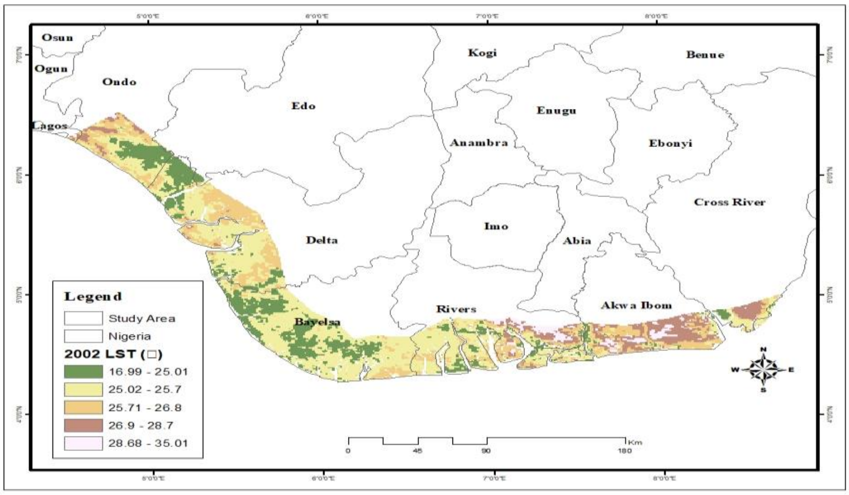


Figure 3. Map showing the spatial Pattern of LST across Niger Delta Region in (2002)

Year 2002 showed increase in the temperature as compared to the year 1987 with the minimum LST of about 16.99ºC while the maximum temperature was about 35.01 ºC.

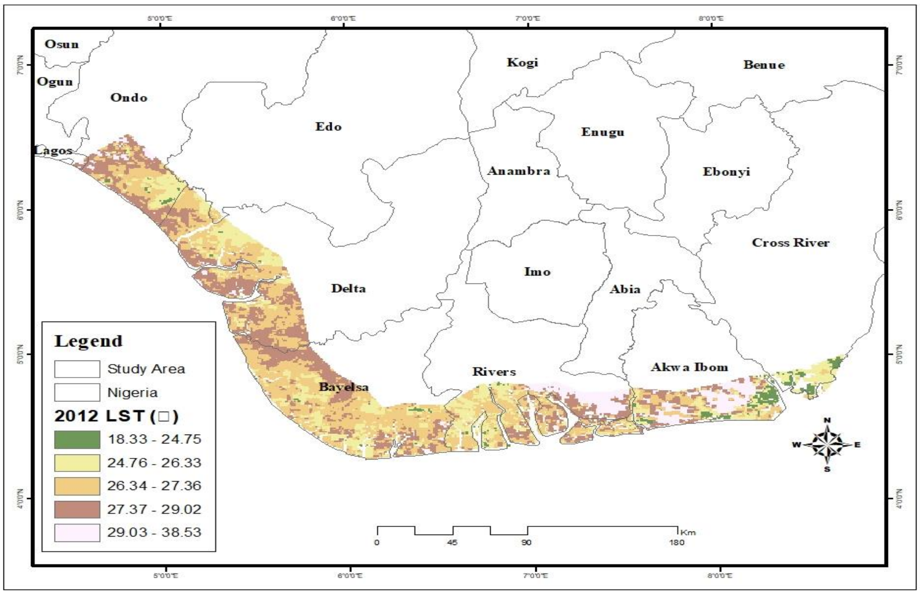


Figure 4: Map showing the spatial Pattern of LST across Niger Delta Region in (2012)

In the year 2012, the land surface temperature further increases as compared to the year 1987 and 2002 with the minimum LST of about 18.33ºC while the maximum temperature was about 38.53 ºC.

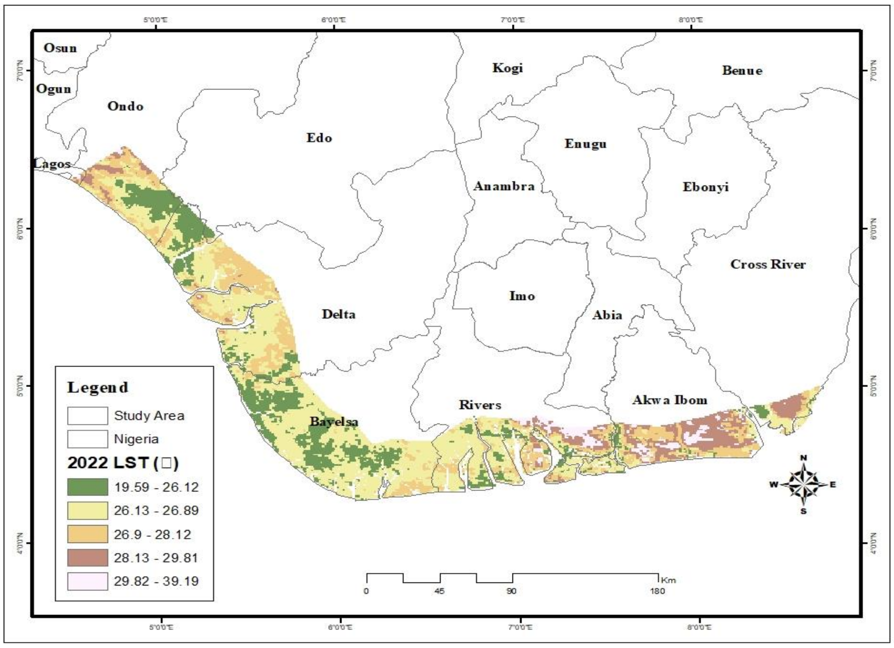


Figure 5. Map showing the spatial Pattern of LST across Niger Delta Region in (2022)

Again, Figure 5 showed increase in the temperature as compared to the year 1987. 2002 & 2012 with the minimum LST of about 19.59ºC while the maximum temperature was about 39.19 ºC.

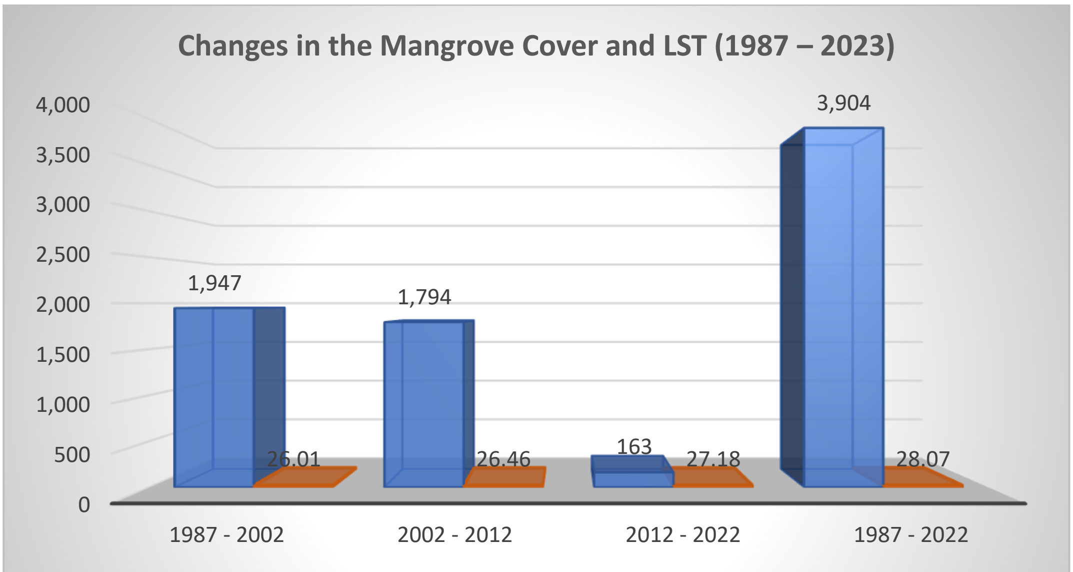
Table 2: Land Surface Temperature from Change in Mangrove Cover of Study Area (1987 – 2022)

Year	Two Limits of LST (ºC)	Average LST (ºC)	Area Km^2	%
1987	16.87 – 24.39	20.63	2164.94	10
	24.39 – 25.62	25.01	5777.53	26
	25.62 – 26.71	26.17	7402.31	34
	26.77 – 28.25	27.51	4476.38	20
	28.25 – 33.20	30.71	2046.84	10
Total	**Overall Average for 1987**	**= 26.01**	**21868**	**100**
2002	16.99 – 25.01	21	1922.19	9
	25.01 – 25.70	25.36	5967.78	26
	25.71 – 26.80	26.26	7332.35	34
	26.90 – 28.70	27.8	4725.67	22
	28.78 – 35.01	31.9	1920.01	9
Total	**Overall Average for 2002**	**= 26.46**	**21868**	**100**
2012	18.33 – 24.75	21.54	981.87	4
	24.76 – 26.33	25.55	5381.71	25
	26.34 – 27.36	26.85	9000.87	41
	27.37 – 29.02	28.2	4786.91	22
	29.03 – 38.53	33.78	1716.64	8
Total	**Overall Average for 2012**	**= 27.18**	**21868**	**100**

2022	19.59 – 26.12 26.13 – 26.89 26.90 – 28.12 28.13 – 29.81 29.82 - 39.19	22.86 26.51 27.51 28.97 34.51	5233.01 9567.25 4301.44 2059.97 706.33	24 44 20 9 3
Total	**Overall Average for 2022**	**= 28.07**	**21868**	**100**

Table 3. Changes in the Mangrove Cover and LST (1987 – 2022)

Time Period	Initial Mangrove Area (Km^2)	Final Mangrove Area (Km^2)	Change in Area (Km^2)	LST (^oC)
1987 - 2002	12,991	11,044	1,947	26.01
2002 - 2012	11,044	9,250	1,794	26.46
2012 - 2022	9,250	9,087	163	27.18
1987 - 2022	12,991	9,087	3,904	28.07
			7,808.00	107.73



	1987 - 2002	2002 - 2012	2012 - 2022	1987 - 2022
Change in Area (Km2)	1,947	1,794	163	3,904
LST (oC)	26.01	26.46	27.18	28.07

Figure 6: Chart showing Changes in the Mangrove Cover and LST (1987 – 2022)

Table 2 and Figure 6 above show changes in the Mangrove Cover and Land Surface Temperature (LST) across four time periods as follows: 1987 – 2002, 2002 – 2012, 2012 – 2022 and 1987 – 2022 respectively. During the period 1987 - 2002, the entire mangrove areas in the Niger Delta Region decreased by 1,947 km² (from 12,991 km² to 11,044 km²). Correspondingly, the LST rose slightly to an initial of 26.01°C. Between 2002 – 2012, the mangrove area further declined by 1,794 km², reducing the total to 9,250 km² and again, the LST increased to 26.46°C, suggesting a rising trend in surface temperatures as mangrove areas shrink. Between 2012 and 2022, the decline in mangrove area slowed down, with a decrease of just 163 km². However, the LST saw a noticeable rise to 27.18°C, continuing the trend of increasing temperatures. Overall, over the whole period of 1987 - 2022, the result of the study showed a significant loss of 3,904 km² in mangrove cover, bringing the total area to 9,087 km² by 2022 and correspondingly, the LST increased substantially to 28.07°C.

Inferring from the foregoing, there appears to be an inverse relationship such that as mangrove cover decreases, the LST increases, highlighting the importance of mangroves in moderating land surface temperatures. The data therefore explains the crucial role plays by mangroves in regulating coastal temperatures by absorbing heat, storing carbon, and promoting moisture in the atmosphere. In the case of the Niger Delta Region of Nigeria, the reduction in mangrove cover due to several land-use and anthropogenic activities has exposed more land, leading to increased surface temperatures due to reduced shading, increased solar radiation absorption, and lower humidity in the area and thus the loss of mangroves likely contributed to the increase in LST. This position agrees with the report of (Mallick *et al*., (2008) that most imperative problem in the earth especially urban halves is increasing surface temperature due to conversion of vegetated surfaces to impervious surfaces, transformation of vegetated and wetland into agricultural land or bare waste land. According to Pal *et al.*, (2009), these changes affect the degree of absorption of solar radiation, reflective power, surface temperature, evaporation rates, transmission of heat to the soil, storage of heat, wind turbulence, and can drastically alter the conditions of the near-surface atmosphere over the cities, modify energy and water balance processes (Oke, 1987) and also play vital role in many environmental processes (Weng *et al*., 2004).

The continued reduction in mangrove cover between 2002 and 2012 correlates with another rise in LST which is likely due to the cumulative effects of habitat loss, where deforested or degraded areas absorb more heat, and the absence of mangroves reduces cooling mechanisms like transpiration and moisture retention. Even with minimal loss in mangrove area between 2012 and 2022, the rising LST indicates a possible lag in the ecosystem's recovery or resilience. Once mangroves are lost, the cooling benefits they provide may take time to regenerate and this is supported by the publication of Walters *et al*. (2008) who reviewed the recovery of ecosystem services following mangrove deforestation and found that cooling benefits, along with other services like water regulation and habitat provision, take time to regenerate fully. The delay can be worsened by environmental stressors such as salinity and pollution. The degraded land may still be contributing to heat retention, and environmental factors like climate change may exacerbate the warming effect.

As mangrove cover decreases, the LST steadily increases which suggests that mangroves play a role in regulating land surface temperatures, possibly due to their ability to absorb heat and their role in coastal ecosystem functions. This conclusion agrees with the investigation of Hathway *et al*., (2012) on the role of the presence of river or water bodies on moderating urban heat island in which he suggested the making of space for water bodies while designing urban area for eco-climatic urban growth. The reduction in mangrove cover could lead to increased exposure of land surfaces, which tend to absorb more heat, thus raising the LST and this is in agreement with Kauffman, *et al*. (2014) who noted that mangrove ecosystems can sequester large amounts of carbon, and when they are degraded, the release of carbon and the exposure of previously shaded soils can lead to significant increases in surface temperature. The slower rate of mangrove loss from 2012 to 2022 may indicate efforts to preserve mangroves, but the rising LST suggests a lag in ecosystem response or other environmental factors influencing temperature. This again is in line with the publication of Walters, *et al*. (2008) who reviewed the recovery of ecosystem services following mangrove deforestation and found that cooling benefits, along with other services like water regulation and habitat provision, take time to regenerate fully and that the delay can be exacerbated by environmental stressors such as salinity and pollution.

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 land surface temperature, highlighting the critical role mangroves play in climate change. The long-term loss of mangrove cover over the period of 35 years from 1987 t0 2022 has led to a marked increase in LST. Consequently, the cumulative reduction in mangroves in the Niger Delta Region diminishes the region’s natural cooling systems, allowing more heat to be absorbed by the exposed land. The loss of mangroves also contributes to higher carbon emissions, which may have localized warming effects. This position is in consonance with Donato, *et al*. (2011) who found that mangroves store significant amounts of carbon, and that their loss can lead to elevated CO_2 levels, which not only contributes to global warming but also has localized impacts on land surface temperatures. Additionally, mangroves help prevent erosion, and their degradation may lead to further environmental changes that compound the rise in temperature.

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).

Disclaimer (artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing interests

Authors have declared that no competing interests exist.

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