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Research Article

Assessing the Impact of Climate Change on Selected Earth Processes in Osun State, Nigeria: Mitigation and Adaptation Strategies

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Abstract

Climate change poses significant threats to the environment, human health, and socioeconomic development. Rising temperatures, erratic rainfall patterns, flooding, and soil degradation have far-reaching consequences for overall livelihoods. Effective mitigation and adaptation strategies are essential to prioritize environmental sustainability and socioeconomic development. This study assessed the effects of climate change on selected earth processes (precipitation, temperature, wind speed, relative humidity) that affect atmospheric and land surface conditions in Osun State, Nigeria, with a view to developing targeted mitigation strategies. The objectives include examining trends in carbon stock and land use, analyzing the dynamics of land use and land cover changes, identifying areas of vulnerability, and developing a framework for integrating mitigation and adaptation strategies. The study used datasets from MERRA-2, the United Nations World Conservation Monitoring Centre, and Landsat imagery to assess the impacts of climate change on processes that affect atmospheric and land conditions. Results show a gradual warming trend, with mean monthly temperatures fluctuating between 24.4 ℃ and 25.34 ℃, and increasing climate variability. The study also found significant declines in vegetation cover, from 77.5% in 2003 to 56.16% in 2023, correlating with increased cropland area and urbanization. The loss of vegetation has direct implications for carbon stock, with biomass reduction diminishing the landscape's ability to store carbon. The analysis also revealed substantial changes in land use patterns, including a significant reduction in vegetation due to urban sprawl and agricultural expansion. The study identifies areas experiencing the greatest loss in vegetation and carbon stock as most vulnerable to climate change impacts. A framework for mitigation and adaptation is proposed, including integrated strategies for sustainability. The findings provide valuable insights for policymakers, stakeholders, and communities to develop and implement sustainable practices that balance development with environmental sustainability.

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Keywords

Climate Change, Temperature, Precipitation, Carbon Stock, Vegetal Cover

1. Introduction

The future of our planet is under threat from the intertwined crises of climate change and environmental destruction [18]. The relentless pursuit of development, driven by a growing global population, has led to the degradation of natural systems and the exacerbation of climate change. Since the Industrial Revolution, the global economy has been fueled by the extraction of natural resources and the burning of fossil fuels, resulting in widespread environmental change. Urbanization, intensive agriculture, and land-use changes have taken precedence over forestation, leading to a significant loss of biodiversity and ecosystem disruption [17].

Climate change is one of the most pressing global challenges of the 21st century, marked by rising temperatures, shifting weather patterns, and an increasing frequency of extreme events. In response, the global community is transitioning from fossil fuels to renewable energy sources, such as solar, wind, and hydropower, to reduce carbon emissions [24]. Understanding carbon stocks, which refer to the quantity of carbon stored in pools such as forests, soils, oceans, and the atmosphere, is crucial for addressing climate change. The global carbon cycle, which regulates the Earth's climate and supports life, is intricately linked to carbon stocks.

Recent advancements in technology and scientific research offer promising opportunities for better understanding and managing carbon stocks. Remote sensing technologies enable accurate monitoring of carbon pools, while innovations in carbon capture provide scalable solutions for reducing emissions. Collaborative efforts between governments, industries, and civil society are essential for scaling these solutions and ensuring a sustainable future. Investments in energy storage technologies and grid modernization are critical to supporting this transition [19].

The Earth's atmosphere is shaped by a delicate balance of natural and human-induced emissions, which in turn influence the planet's climate system. The atmosphere's composition is characterized by a stable mixture of gases, with nitrogen, oxygen, and noble gases making up over 99.2% of its molecules, excluding water vapor, [7]. These gases have remained relatively constant over the past billion years, providing a steady foundation for the atmosphere. However, a small fraction of the atmosphere, comprising less than 0.1% of its molecules, including carbon dioxide (CO_2) and methane (CH_4), plays a disproportionate role in regulating critical atmospheric processes, such as climate change, [13].

The Industrial Revolution has marked a significant turning point in the Earth's climate history, with human activities leading to a substantial increase in greenhouse gases (GHGs) in the atmosphere [22]. As of 2019, the concentrations of CO_2, CH_4, and N_2O (nitrogen oxide) had reached 410 ppm, 1866 ppb, and 332 ppb, respectively [12]. CO_2, a crucial component of the Earth's radiation balance and the primary feedstock for photosynthesis, has been particularly impacted. Between 1850 and 2019, human activities released approximately 2390 ± 240 $GtCO_2$ (gigatonnes of carbon dioxide) of anthropogenic CO_2 into the atmosphere [4]. One of the earliest works showing the impact of earth processes on climate was demonstrated by the effect of carbonic acid in the air upon the temperature of the ground [5]. The emission of GHGs and particulate matter has been dispersed by winds, influencing the atmosphere's temperature structure and climate through radiative absorption [25]. The resulting 0.6 °C rise in global surface air temperature during the 20th century has been largely attributed to the increasing atmospheric concentration of GHGs, which has also caused significant changes in the mesosphere, thermosphere, and ionosphere, including a thermal contraction of these layers [10, 11]. Furthermore, current estimates of climate sensitivity suggest that a 100 ppm increase in atmospheric CO_2 is associated with a temperature increase of approximately 1℃ (degrees centigrade), highlighting the critical need to mitigate GHG emissions and address the ongoing climate crisis [12].

The study [6] utilized six Dynamic Global Vegetation Models to demonstrate that, while elevated CO_2 enhances terrestrial carbon sinks, climate change significantly reduces this sink by 2100 due to declining Net Ecosystem Production (NEP). The study found that long-term climate-induced changes in vegetation structure may cause the land sink to be lower than predicted by CO_2-only simulations. The importance of climate change adaptation strategies, in conjunction with mitigation efforts, is increasingly recognized by professionals as crucial for addressing the challenges posed by global warming, [12]. Even if all human-induced emissions were to cease immediately, the climate would continue to change, underscoring the need for adaptation measures. Given the delayed impact of mitigation efforts on rising temperatures, which will take decades to materialize, it is essential to undertake a transformative shift in global systems to adapt to the ongoing and anticipated changes. This necessitates the development and implementation of comprehensive strategies across all global development systems, with the aim of enhancing resilience and adapting to the inevitable effects of climate change.

To mitigate the impacts of climate change, a range of strategies can be employed. For instance, constructing coastal sea walls can help protect coastal communities from the encroaching threat of rising sea levels, while developing drought-resistant crops can aid in combating water scarcity [8]. [9] and [14] argue that achieving increased adaptation action will necessitate integration of climate change-related issues with other risk factors, such as climate variability and market risk, and with other policy domains, such as sustainable development. [21] maintained that agriculture has a significant, untapped potential to mitigate climate change, providing technical and economic potential for reducing greenhouse gases (GHGs) via soil carbon sequestration, improved land management, and livestock management. In preparation for extreme weather events, advanced technologies such as high-resolution monitoring and simulation, as well as satellite-based remote sensing, can be leveraged to develop sophisticated Earth system and climate models. These models, informed by current and historical data, can provide critical insights into the frequency and severity of extreme weather events, enabling predictions about when and where they are likely to occur [3], as well as the magnitude of their impact.

By utilizing these predictive models, it is possible to take proactive measures to protect people and the environment in high-risk areas, provided that effective warning systems are in place, [20]. Moreover, adapting to the effects of climate change requires a multifaceted approach that includes raising public awareness about how to cope with these impacts, enhancing response capabilities, and reducing overall risk and vulnerability. Collaboration among citizens, researchers, and policymakers is essential for developing and implementing effective climate change adaptation measures at various levels. By working together, it is possible to identify and prioritize specific actions that can be taken to build resilience and promote sustainable development in the face of a changing climate.

Numerous studies have been conducted in the field of climate change adaptation and mitigation strategies, as well as the impact of carbon stocks on the environment. Carbon stocks play a crucial role in regulating the Earth's climate by storing carbon, and ecosystems help mitigate the effects of greenhouse gas (GHG) emissions, which trap heat in the atmosphere and lead to global warming. The balance between carbon sources (emitting CO_2) and sinks (absorbing CO_2) determines the stability of atmospheric carbon, influencing climate stability [2]. [23] assessed climate change adaptation and mitigation strategies in Lagos State, Nigeria, from the perspective of built environment professionals. The study revealed that the professionals identified the main causes of climate change as the use of fossil fuels in industrial production, automobiles, and electricity generation. The top three adaptation and mitigation strategies identified were greening/planting trees, enforcement of building guidelines, and the use of energy-efficient technologies.

Additionally, [23] examined climate change mitigation and adaptation strategies for construction activities within planetary boundaries, with a focus on the limitations faced by developing countries. The study recommends the use of green energy, sustainable building materials, high-rise buildings, innovative designs and construction methods, and recycling of urban waste. The paper also argues that developing countries are highly vulnerable to climate change effects, but face limitations in mitigating and adapting to climate change. Finally, [15] assessed carbon management and sequestration, suggesting the use of developed technologies to reduce the rate of increase of atmospheric CO_2 concentrations. The study discusses the use of low- or no-carbon fuel, sequestration of emissions, and processes for carbon (CO_2) sequestration, including abiotic and biotic technologies. Carbon sequestration involves the transfer of atmospheric CO_2 into other long-lived global pools, including oceanic, pedologic, biotic, and geological strata, to reduce the net rate of increase in atmospheric CO_2. Abiotic techniques include engineering methods such as CO_2 injection into deep oceans, geological strata, old coal mines, and oil wells, as well as mineral carbonation of CO_2.

Osun State, located in southwestern Nigeria, is vulnerable to the impacts of climate change, including rising temperatures, erratic rainfall patterns, flooding, and soil degradation. These changes have far-reaching consequences for human health, agriculture, water resources, and overall livelihoods. To address these challenges, it is essential to adopt effective mitigation and adaptation strategies that prioritize environmental sustainability and socioeconomic development. This study reviews the adaptation and mitigation strategies for climate change effects in Osun State, Nigeria, with a focus on identifying opportunities for sustainable development and environmental resilience.

The central objective of the study is to investigate the effects of climate change on Earth's processes and to identify and develop targeted mitigation strategies to reduce the drivers of climate change and promote sustainable development in Osun State, Nigeria. The specific objectives of the study are: to assess the current impacts of climate change on earth's processes, such as precipitation, temperature, and weather pattern events, between 1994 and 2023; to examine the trends of carbon stock, biomass, and vegetal covers in the study area; to analyze the dynamics of land use and land cover in Osun State; to identify areas of vulnerability and prioritize regions for targeted mitigation and adaptability strategies; and to develop a framework for integrating mitigation and adaptability strategies for sustainable development.

2. Materials and Methods

2.1. Study Area

The study area shapefile was obtained from Geo-Referenced Infrastructure and Demographic Data for Development (GRID3) and Osun State is located between latitude 7°51’15” N and 7°30’12” N and longitude 4°12’25” E and 4°35’10” E.

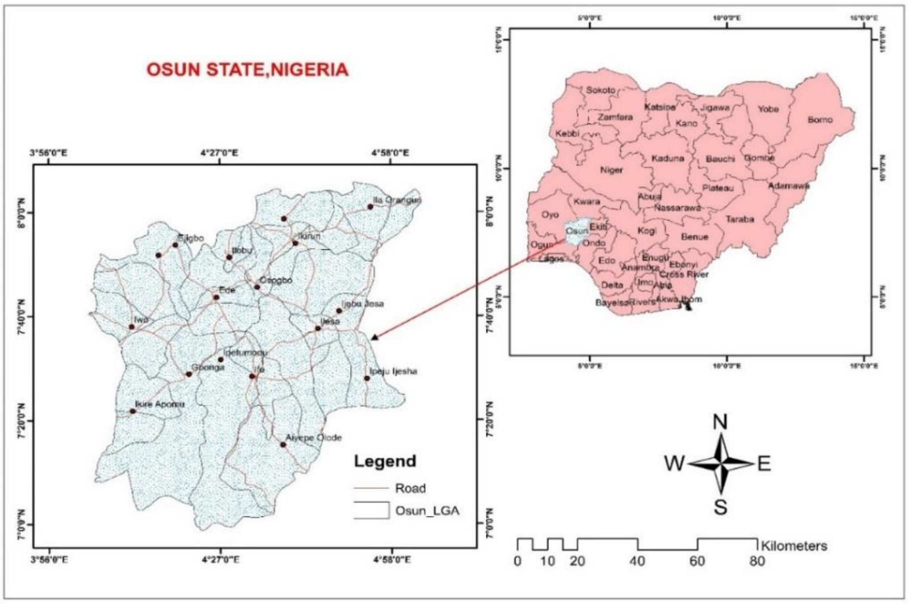

Figure 1. *Study Area Map.*

2.2. Data Requirements

To assess the impacts of climate change on Earth's processes, secondary data (climate satellite data) was obtained from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) for precipitation, temperature, wind, and relative humidity data at 2-meter resolutions. MERRA-2 is a reanalysis dataset produced by NASA's Global Modeling and Assimilation Office (GMAO) that provides a multidecadal reanalysis of atmospheric and land surface conditions. To examine the trends of carbon stock biomass and vegetal covers, the above- and below-ground terrestrial carbon storage global carbon biomass referenced 2010 was obtained from the United Nations World Conservation Monitoring Centre. This dataset represents above- and below-ground terrestrial carbon storage (tonnes of C per hectare) for circa 2010 and was constructed by combining publicly available datasets and overlaying them with the ESA CCI land cover map for 2010. For land use and land cover changes, secondary data (satellite imageries) of 30m resolution from Landsat 5, Landsat 7, and Landsat 9 were obtained from the United States Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA) website. These data were used to carry out land use and land cover classification and examine potential changes that occurred between 1994 and 2023 over Osun State, Nigeria.

The datasets used in this study include: MERRA-2 for climate data, United Nations World Conservation Monitoring Centre for carbon stock biomass data and Landsat 5, Landsat 7, and Landsat 9 for land use and land cover data. These datasets provide global, sub-daily estimates of atmospheric and land surface conditions, as well as information on carbon stock biomass and land use and land cover changes, which are essential for understanding the impacts of climate change on Earth's processes.

2.3. Data Analysis

To achieve the trends of climate variables over the Osun State between 1994 -2023, a geo-statistical method was used to assess the climate change variability over a period of 30 years and we analyzed the data based on ten years' interval starting from 1994. Kriging interpolation approach was used to create a uniform surface for climate variability of the study area. Kriging is a method of spatial interpolation that originated in the field of mining geology as was named after South African mining engineer Danie Krige. In a general sense, the spatial covariance structure of the sampled points is determined by fitting a variogram; and second, weights derived from this covariance.

2.3.1. Climate Variables

The data were converted to NetCDF format and then to a raster layer using the Multidimensional Tool in ArcGIS software. The raster data were then exported in GeoTIFF format, and the Cell Statistics tool in the Arc Toolbox was used to calculate the mean annual average of the raster data for every ten years, starting from 1983 to 2023. After obtaining the annual mean for every ten years, the raster data were converted to point features, and then interpolated using the Kriging method.

2.3.2. Carbon Stock Biomass

For the carbon stock biomass, the regression analysis in the google earth engine API was used to extra carbon stock density of the study for 2003, 2012 and 2023 using global carbon stock referenced 2010 from United Nations World Conservation Monitoring Centre together with normalized difference vegetation index (NDVI).

2.3.3. Dynamics of Land Use and Land Cover

Land use and land cover changes for adaptation and mitigation strategies for climate change effects in Osun State, Nigeria, a supervised maximum likelihood classification method was used to classify the land use and land cover of the study area into built-up area, cropland, vegetation, rock-outcrop and water body. *A* Supervised classification is the process of assigning a class value to a set of grid cells in a raster data based on the values of similar grid cells that have been *a prior* classified as representative of a class or group [1]. This process is called supervised classification because it requires a person to manually interpret a satellite or aerial image and define groups of grid cells, called *training sets*, that share similar spectral reflectance values. A training set should include grid cells that are homogenous and representative of various features of interest across the landscape. Using a multi-spectral image with multiple bands of electromagnetic imagery, the range of numerical spectral signature values ranging from (red, green, blue, near-infrared (NIR), and other bands collected by a particular sensor) for each class are used to define which grid cells in an image are members of the same class [16]. Maximum likelihood classification assumes that the statistics for each class in each band are normally distributed and calculates the probability that a given pixel belongs to a specific class. Unless you select a probability threshold, all pixels are classified. Each pixel is assigned to the class that has the highest probability (that is, the maximum likelihood). If the highest probability is smaller than a threshold you specified, the pixel remains unclassified.

3. Results and Discussion

This study demonstrates that climate change in Osun State is occurring alongside marked land surface transformation, and that the two processes are reinforcing one another. Over the study period, the climatic variables examined showed evidence of increasing variability, while land use analysis revealed a sustained decline in vegetation cover, expansion of cropland, growth of built-up areas, and a corresponding reduction in carbon storage potential. Taken together, these findings suggest that climate risk in Osun State cannot be understood only in terms of changing atmospheric conditions; it is also being intensified by how land is being converted and managed. The significance of this interaction is that it affects ecological stability, agricultural productivity, flood susceptibility, and the long-term environmental resilience of Osun State.

3.1. Assessment of Climate Change Impacts on Earth's Processes

3.1.1. Temperature Variability (1994-2023)

The temperature record shows a gradual warming tendency across the study period. As presented in Table 1, mean monthly temperature ranged from 24.44 ℃ in 1994 to a peak of 25.34 ℃ in 2016, while most recent years remained generally above the earliest values. The spatial pattern in Figure 2 and the spread between annual maximum and minimum temperatures in Table 2 and Figure 3 further indicate that the issue is not only a slight rise in average temperature, but also increasing thermal variability. This interpretation is consistent with the wider climate literature, which shows that with increasing warming, the frequency and intensity of hot extremes tend to rise.

For Osun State, this warming trend has practical implications for agriculture, water balance, and human well-being. Higher temperatures can increase evapotranspiration, intensify soil moisture loss, and reduce the capacity of already stressed landscapes to retain water. In areas experiencing ongoing vegetation clearance, local warming may also be amplified because vegetated surfaces generally moderate land surface temperature more effectively than bare or built-up surfaces. This means that the warming signal shown in Table 1 and Figure 3 is likely to translate into increased environmental stress where land conversion is already advanced.

Table 1. *Mean Monthly Temperature (1994-2023).*

YEAR	Mean Monthly Temperature (℃)	YEAR	Mean Monthly Temperature (℃)
1994	24.44	2009	24.92
1995	24.62	2010	25.11
1996	24.71	2011	24.65
1997	24.73	2012	24.58
1998	25.23	2013	24.73
1999	24.74	2014	24.98

YEAR	Mean Monthly Temperature (℃)	YEAR	Mean Monthly Temperature (℃)
2000	24.90	2015	24.80
2001	25.05	2016	25.34
2002	25.12	2017	25.12
2003	25.03	2018	24.82
2004	24.93	2019	25.07
2005	25.05	2020	24.93
2006	25.32	2021	25.13
2007	24.80	2022	24.59
2008	24.66	2023	24.45

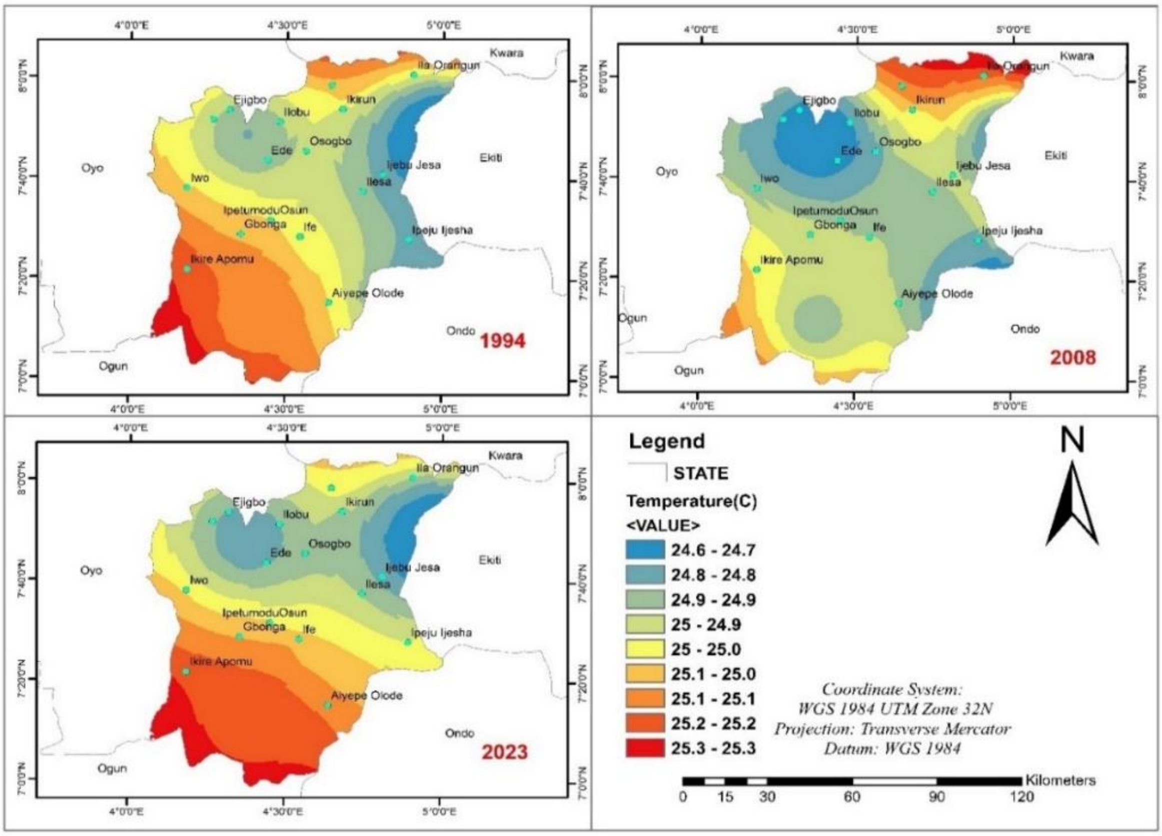

Figure 2. Map showing Temperature Pattern (1994-2023).

Table 2. Table showing Maximum and Minimum Temperature (1994-2023).

Year/Temp	Max	Min	SD	CV	Year/Temp	Max	Min	SD	CV
1994	35.19	13.96	11.4423	46.56072	2009	33.07	16.65	9.923874	39.91904
1995	34.12	15.83	10.35393	41.45716	2010	33.54	15.62	10.69623	43.51599
1996	34.34	16.79	11.04572	43.20641	2011	32.35	13.39	10.90218	47.67023
1997	35.64	15.05	12.35098	48.73142	2012	33.27	14.52	10.62084	44.44796
1998	36.79	14.63	11.71264	45.55675	2013	32.39	14.37	10.44232	44.66346

Year/Temp	Max	Min	SD	CV	Year/Temp	Max	Min	SD	CV
1999	33.27	15.17	11.87175	49.01629	2014	33.83	15.79	11.78754	47.51124
2000	37.37	14.76	12.64297	48.50554	2015	33.84	11.5	13.01823	57.42492
2001	36.41	15.25	12.69685	49.15543	2016	37.02	14.72	11.62565	44.93872
2002	36.97	14.18	12.81988	50.12659	2017	34.12	16.43	10.95194	43.33114
2003	36.10	14.5	11.5241	45.54979	2018	33.44	13.44	10.95485	46.73571
2004	34.14	15.97	11.54316	46.07127	2019	32.37	14.48	11.4038	48.68217
2005	34.19	12.65	13.21335	56.4191	2020	34.4	12.95	11.62998	49.12347
2006	37.90	14.01	13.42991	51.74307	2021	34.68	16.09	11.10754	43.75633
2007	35.67	13.16	12.34006	50.54295	2022	32.94	13.33	11.16533	48.26162
2008	33.25	13.15	14.21285	61.26227	2023	33.56	14.54	13.44981	55.92345

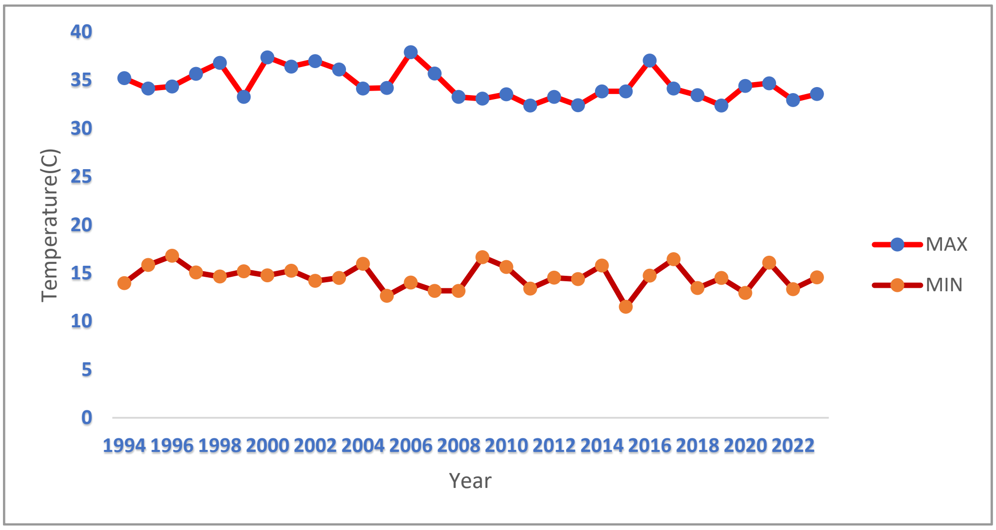

Figure 3. *Graph of Maximum and Minimum Temperature (1994-2023).*

3.1.2. Precipitation Patterns (1994-2023)

Rainfall showed strong interannual variability over the period of analysis. As shown in Table 3 and Figure 5, mean monthly precipitation declined to 94mm in 2005 but rose sharply to 312mm in 2023, indicating a much less stable hydroclimatic regime in recent years. Table 4 reinforces this pattern by showing that the 2023 rainfall value had the highest rank and the longest estimated return period in the series. The spatial pattern in Figure 4 and the relationship presented in Figure 6 suggest that rainfall behaviour is becoming more erratic rather than simply wetter or drier. This aligns with broader evidence that warming intensifies the global water cycle and increases the severity of both wet and dry events.

The implication for Osun State is that climate risk is likely to arise from both excess water and water scarcity. Intense rainfall events can increase runoff, flooding, soil erosion, and damage to drainage systems, while lower-rainfall years can disrupt cropping calendars and reduce water availability. The observed rise from moderate rainfall totals in earlier years to very high totals in 2021-2023, as seen in Figure 5, suggests that flood-prone communities and agricultural areas may become increasingly exposed to hydroclimatic shocks. This interpretation is consistent with evidence that changes in streamflow magnitude and flood damages increase where adaptation is weak.

Table 3. Mean Monthly Precipitation (1994-2023).

Year	Mean Monthly Precipitation (mm)	Year	Mean Monthly Precipitation (mm)
1994	154	2009	142
1995	187	2010	176
1996	141	2011	146
1997	161	2012	179
1998	135	2013	125
1999	126	2014	166
2000	105	2015	120
2001	119	2016	163
2002	128	2017	152
2003	138	2018	195
2004	150	2019	222
2005	94	2020	148
2006	135	2021	258
2007	157	2022	224
2008	148	2023	312

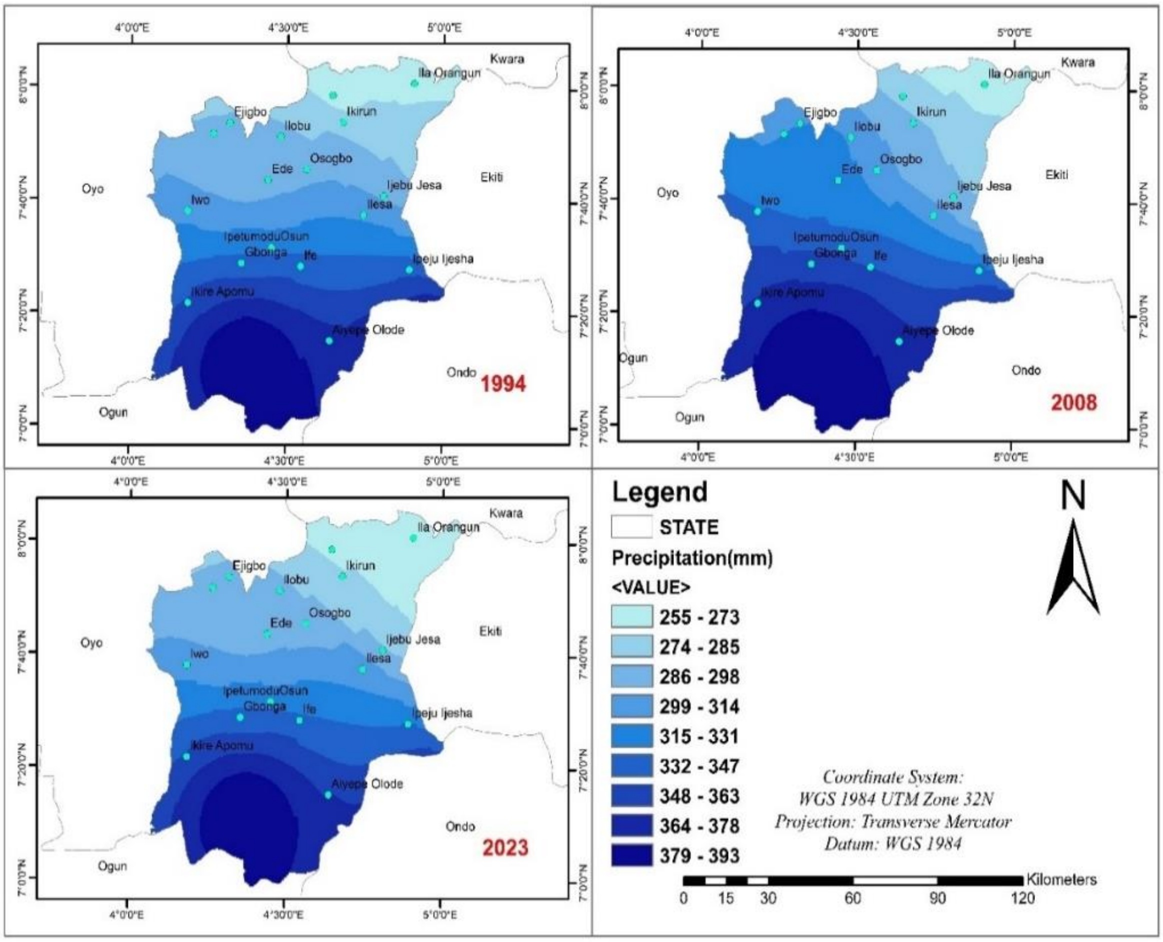

Figure 4. Map showing Precipitation Pattern (1994-2023).

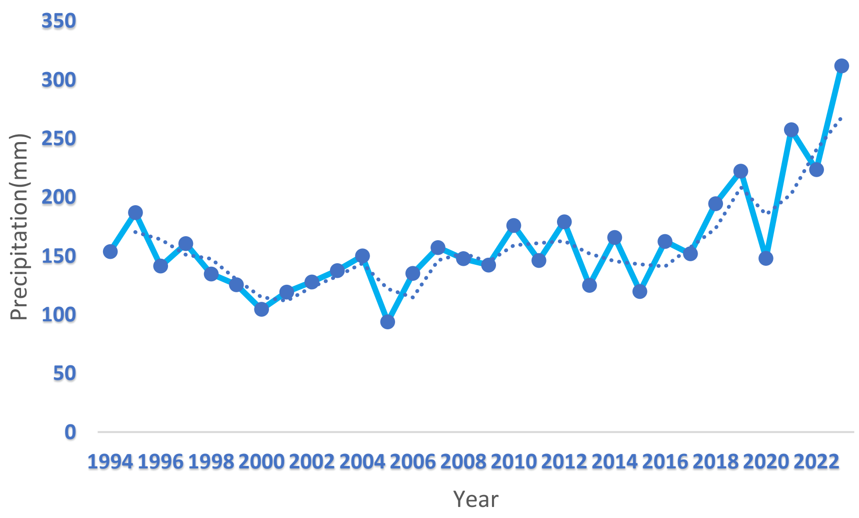

Figure 5. Graph of mean Monthly Precipitation (1994-2023).

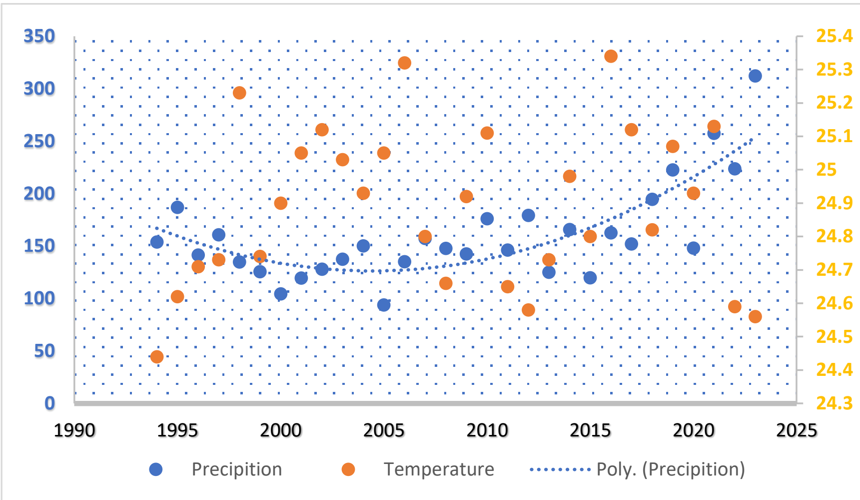

Figure 6. Graph showing correlation between Precipitation and Temperature.

Table 4. Probability and likely-return Period of Precipitation (1994-2023).

Year	Precipitation (mm)	Rank	Pr	RP	Year	Precipitation (mm)	Rank	Pr	RP
1994	154	13	0.4194	2	2009	142	19	0.6129	2
1995	187	6	0.1935	5	2010	176	8	0.2581	4
1996	141	20	0.6452	2	2011	146	18	0.5806	2
1997	161	11	0.3548	3	2012	179	7	0.2258	4
1998	135	23	0.7419	1	2013	125	26	0.8387	1
1999	126	25	0.8065	1	2014	166	9	0.2903	3
2000	105	29	0.9355	1	2015	120	27	0.8710	1
2001	119	28	0.9032	1	2016	163	10	0.3226	3
2002	128	24	0.7742	1	2017	152	14	0.4516	2
2003	138	21	0.6774	1	2018	195	5	0.1613	6
2004	150	15	0.4839	2	2019	222	4	0.1290	8

Year	Precipitation (mm)	Rank	Pr	RP	Year	Precipitation (mm)	Rank	Pr	RP
2005	94	30	0.9677	1	2020	148	17	0.5484	2
2006	135	22	0.7097	1	2021	258	2	0.0645	16
2007	157	12	0.3871	3	2022	224	3	0.0968	10
2008	148	16	0.5161	2	2023	312	1	0.0323	31

3.1.3. Humidity

The humidity series in Table 5 and Figure 8 shows a generally increasing tendency, with values rising from 16.48 g/kg in 1994 to levels mostly above 17 g/kg in many later years. The mapped distribution in Figure 7 also indicates spatial differences in atmospheric moisture across the state. Although humidity often receives less emphasis than temperature and rainfall, it is relevant because rising atmospheric moisture can influence thermal comfort, cloud formation, local weather behaviour, and the intensity of rainfall-producing systems. In a tropical environment, warmer and more humid conditions may increase discomfort, compound heat stress, and contribute to unstable local weather conditions.

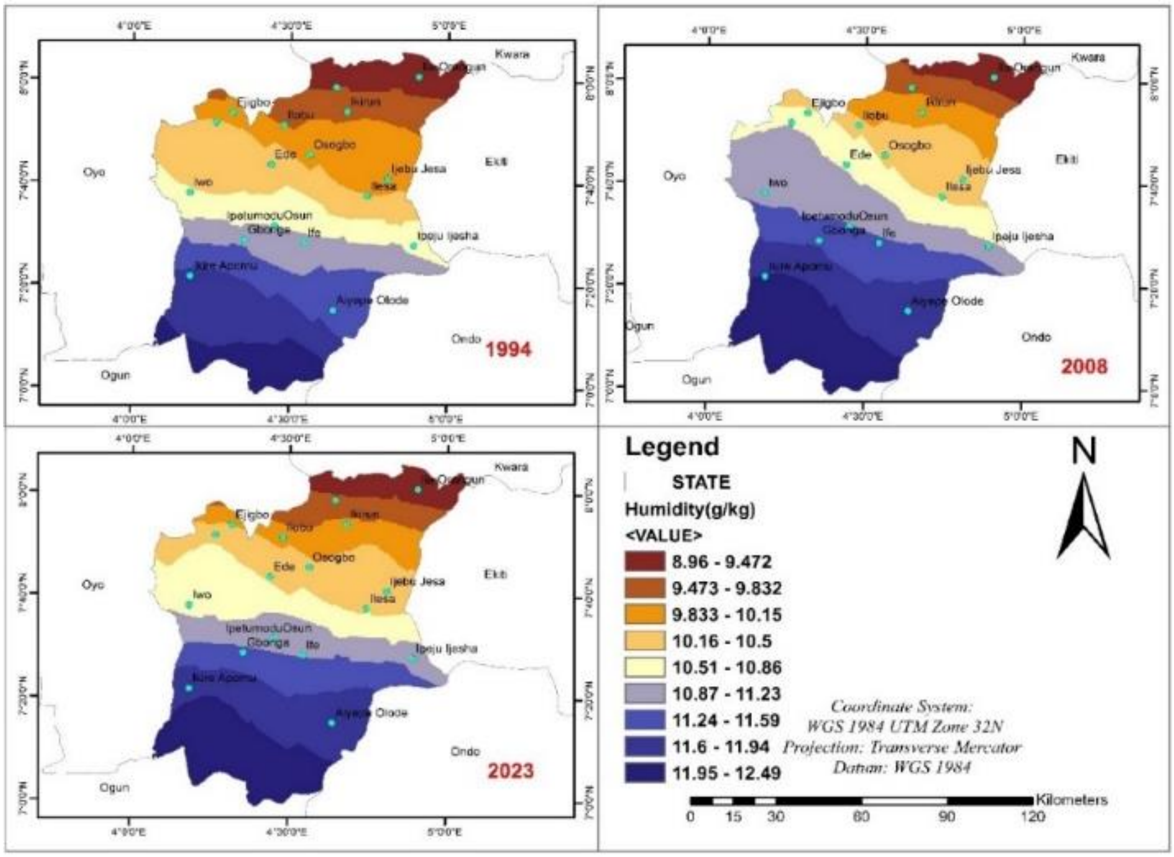

Figure 7. Map showing mean Monthly Humidity Pattern (1994-2023).

Table 5. Mean Monthly Humidity (1994-2023).

Year	Mean Monthly Humidity (g/kg)	Year	Mean Monthly Humidity (g/kg)
1994	16.48	2009	17.46
1995	16.78	2010	17.58

Year	Mean Monthly Humidity (g/kg)	Year	Mean Monthly Humidity (g/kg)
1996	16.78	2011	16.97
1997	16.54	2012	17.03
1998	16.78	2013	17.33
1999	16.91	2014	17.40
2000	15.99	2015	16.97
2001	16.42	2016	17.15
2002	16.60	2017	17.52
2003	17.21	2018	17.09
2004	17.27	2019	17.58
2005	17.40	2020	17.03
2006	17.15	2021	17.52
2007	16.91	2022	17.03
2008	16.72	2023	17.13

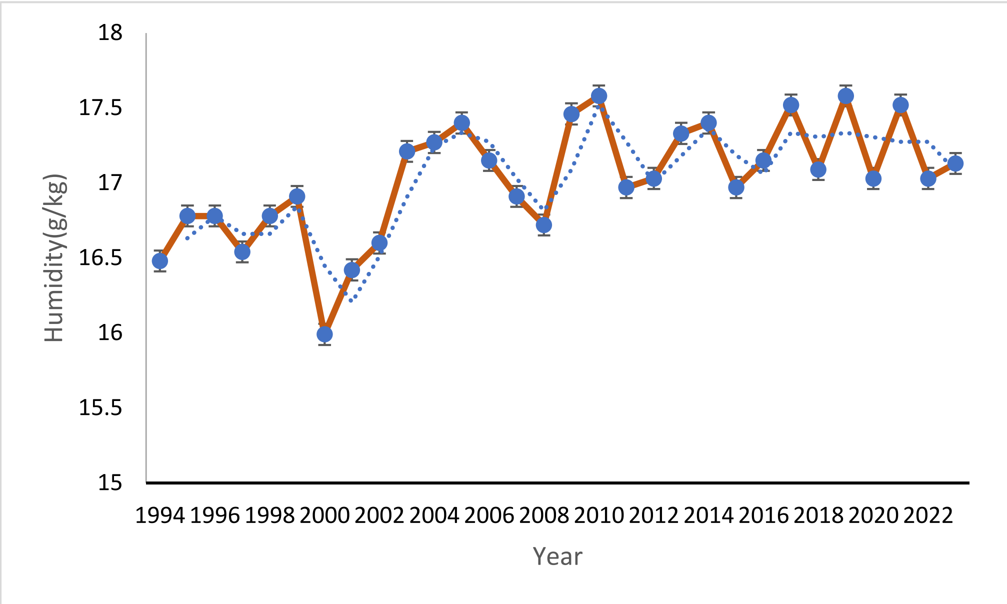

Figure 8. *Graph of mean Monthly Humidity (1994-2023).*

3.1.4. Wind Speed

Wind speed showed a modest but general decline over the study period. According to Table 6, mean monthly wind speed decreased from 1.11 m/s in 1994 to 0.89 m/s in 2023, while Figure 10 indicates that values fluctuated around a gradually declining tendency. The mapped pattern in Figure 9 suggests that these changes are spatially differentiated across Osun State. Although the decline is not dramatic, lower wind speed may reduce near-surface mixing and contribute to warmer and more stagnant local conditions, especially in built-up areas where vegetation is already limited. In the context of rising temperature and humidity, this pattern may further reduce environmental comfort and resilience.

Table 6. The mean Monthly Wind (1994-2023).

Year	Mean Monthly Wind (m/s)	Year	Mean Monthly Wind (m/s)
1994	1.11	2009	0.94
1995	1.04	2010	0.98
1996	1.05	2011	0.96
1997	1.02	2012	1.01
1998	1.05	2013	0.99
1999	1.01	2014	0.97
2000	1.02	2015	1.05
2001	1.03	2016	1.00
2002	1.03	2017	0.92
2003	1.00	2018	0.98
2004	0.98	2019	0.96
2005	1.02	2020	1.05
2006	1.00	2021	0.95
2007	1.01	2022	0.99
2008	0.97	2023	0.89

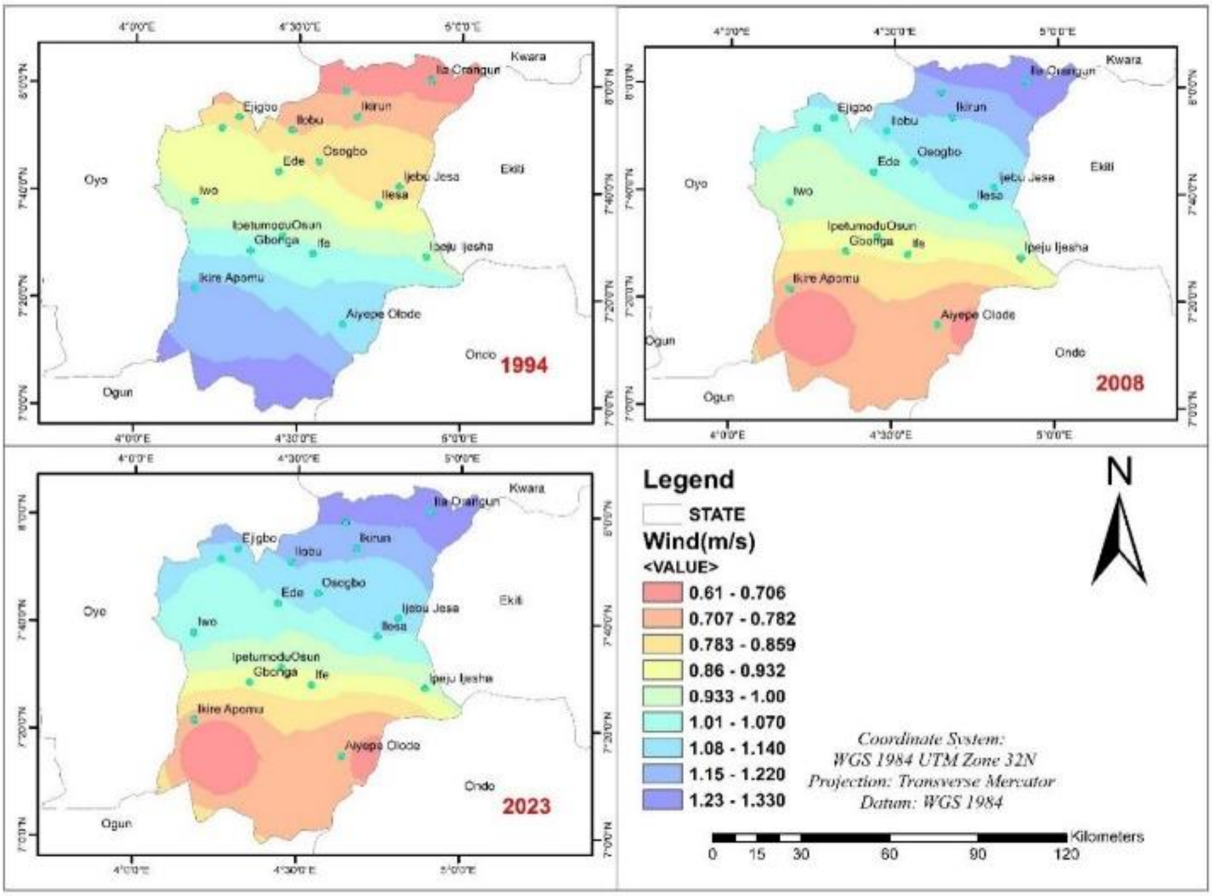

Figure 9. Map showing Wind Pattern (1994-2023).

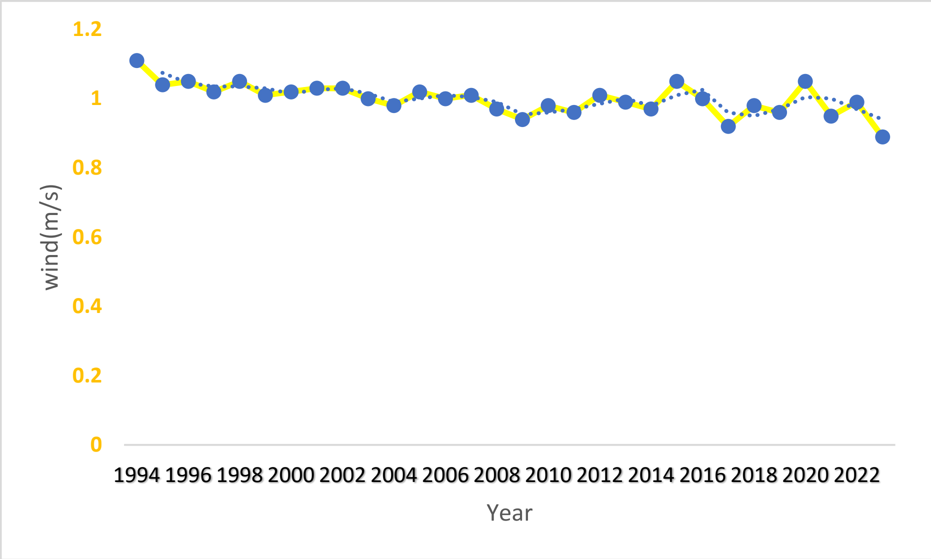

Figure 10. *Graph of mean Monthly Wind Speed (1994-2023).*

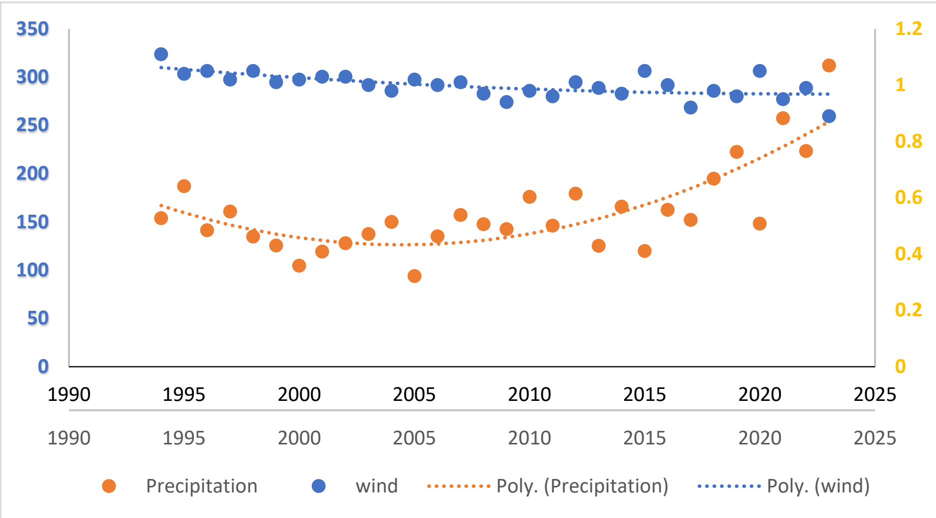

Figure 11. *Graph showing correlation between Precipitation and Wind Speed.*

3.2. Trends of Land Use and Carbon Stock Biomass and Vegetal Covers

3.2.1. Land Use Trends (2003-2023)

The land use results show one of the clearest patterns in the study. Vegetation declined from 77.50% in 2003 (Table 7, Figure 12) to 73.51% in 2012 (Table 8, Figure 14) and then to 56.16% in 2023 (Table 9, Figure 16). Over the same period, cropland increased from 19.40% to 36.68%, while built-up area rose from 2.80% to 6.82%. These changes are clearly illustrated in Figure 18 and indicate sustained conversion of vegetated land into agricultural and urban uses. The NDVI outputs in Figures 19 and 20 support this interpretation by showing a decline in vegetation condition over time.

This pattern is environmentally significant because vegetation performs several climate-regulating functions, including carbon storage, surface cooling, soil protection, and water retention. Its decline therefore weakens the landscape's natural capacity to buffer climatic stress. The increase in cropland suggests rising pressure on land resources, while the growth in built-up area reflects settlement expansion and urbanisation. Neither process is inherently undesirable, but when they occur through unchecked reduction of vegetation, they increase ecological vulnerability and reduce resilience. This is especially important in view of the rainfall and temperature patterns already identified in Tables 1–4 and Figures 3–6.

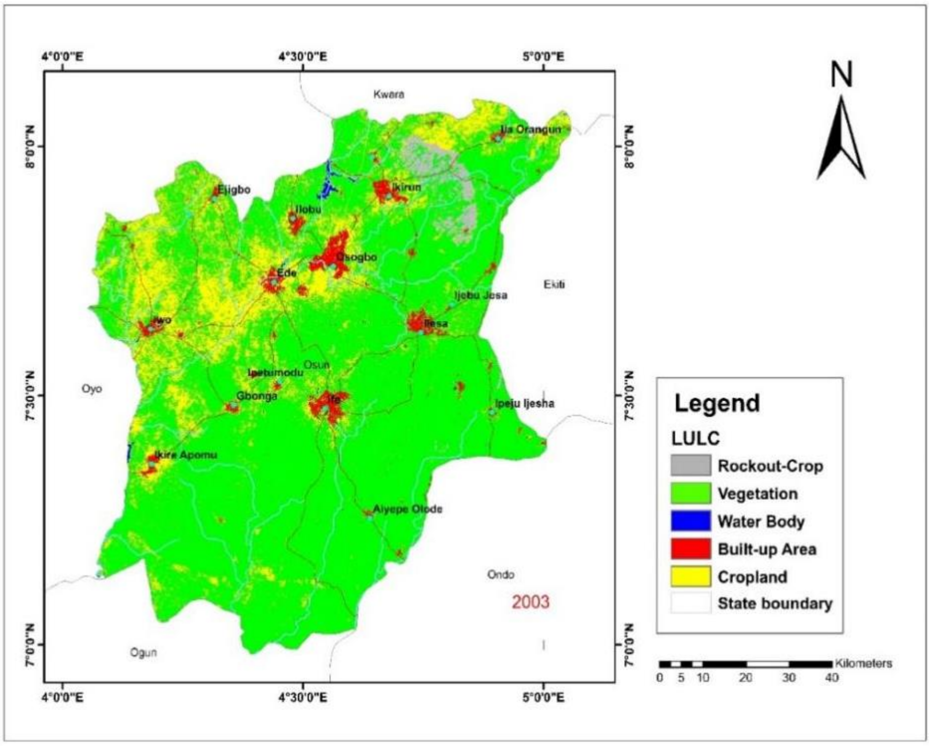

Figure 12. Map showing 2003 Land Use and Land Cover Classification.

Table 7. 2003 Land Use and Land Cover Area.

Classes	Area (km^2) 2003	Percentage (%)
Water	20.20	0.20
Vegetation	6476.30	77.50
Built-up Area	233.65	2.80
Cropland	1621.79	19.40
Rock-out Crop	7.45	0.10%
Total	8359.39	100

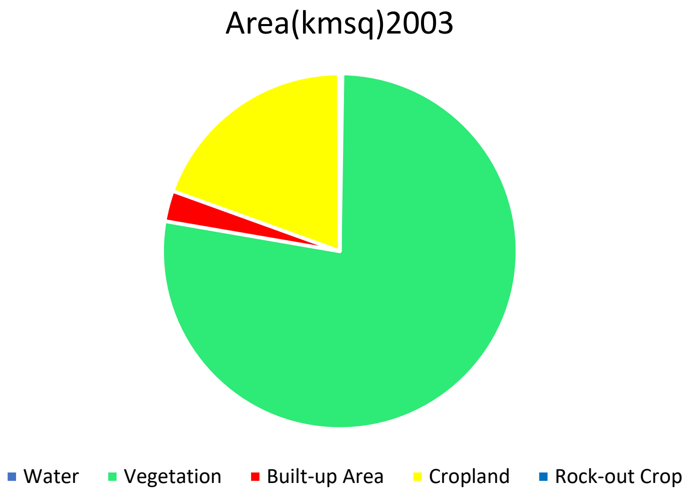

Figure 13. Pie Chart showing 2003 Land Use and Land Cover Classification.

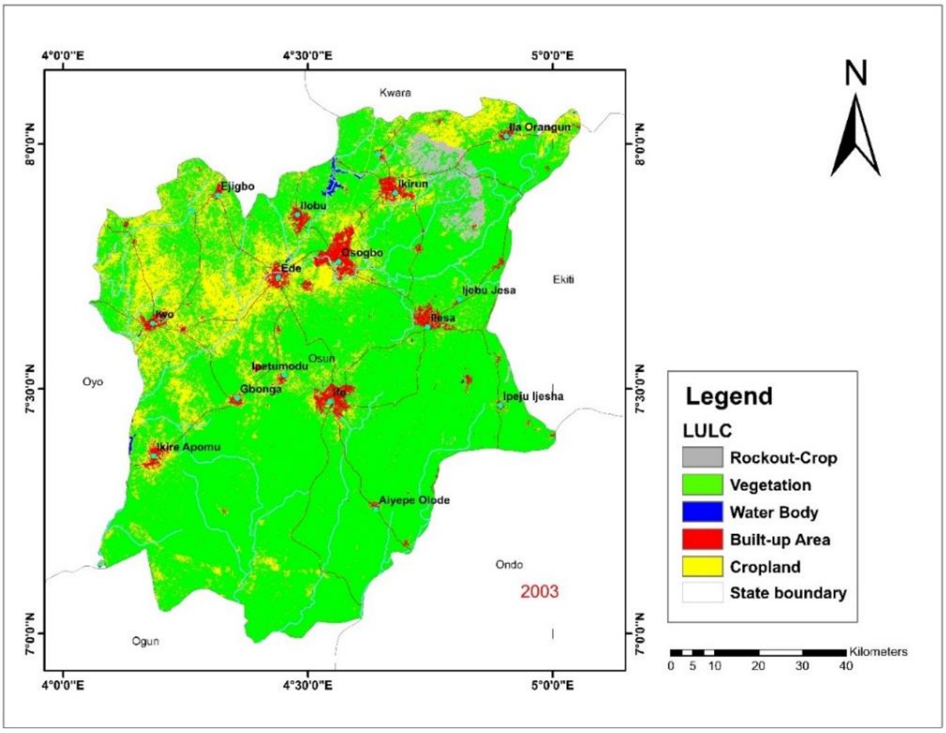

Figure 14. Map showing 2012 Land Use and Land Cover Classification.

Table 8. 2012 Land Use and Land Cover Area.

Class	Area (km^2) 2012	Percentage (%)
Water	19.65	0.24
Vegetation	5954.20	73.51
Built-up Area	304.54	3.76
Cropland	1813.32	22.39
Rock-out Crop	7.10	0.10
Total	8098.81	100%

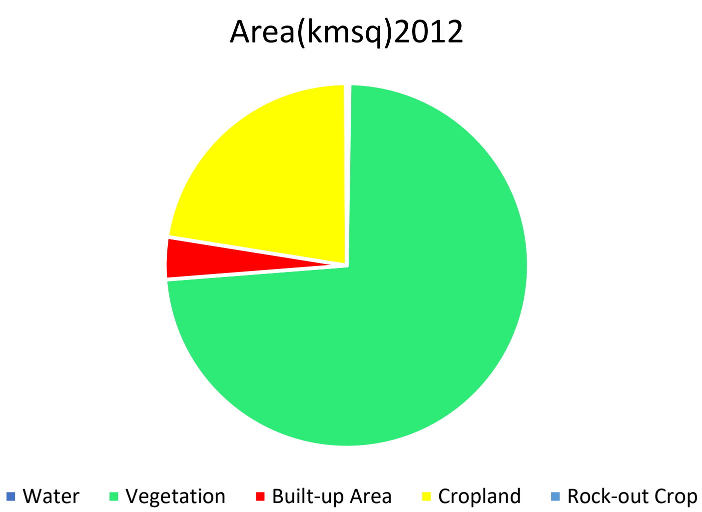

Figure 15. Pie Chart showing 2012 Land Use and Land Cover Classification.

***Table 9**. 2003 Land Use and Land Cover Area.*

CLASS	Area (km^2) 2023	Percentage (%)
Water	17.94	0.24
Vegetation	4154.2	56.16
Built-up Area	504.54	6.82
Cropland	2713.32	36.68
Rock-out Crop	6.89	0.10
Total	7396.89	100%

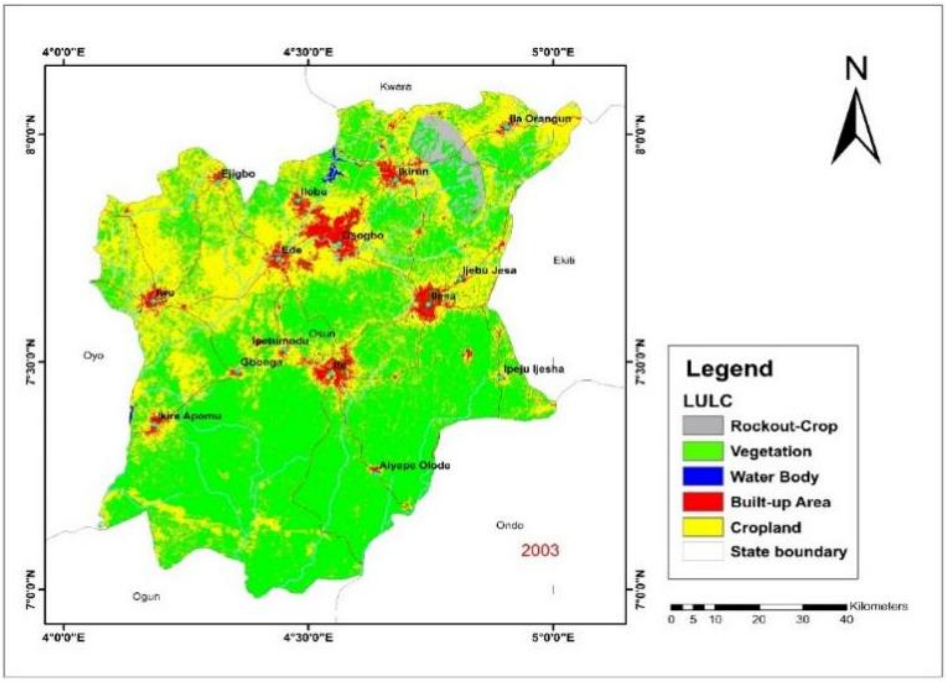

***Figure 16**. Map showing 2023 Land Use and Land Cover Classification.*

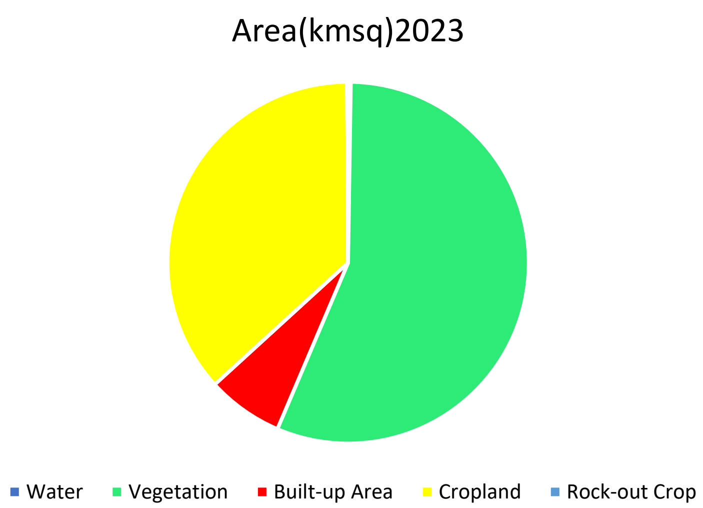

***Figure 17**. Pie Chart showing 2012 Land Use and Land Cover Classification.*

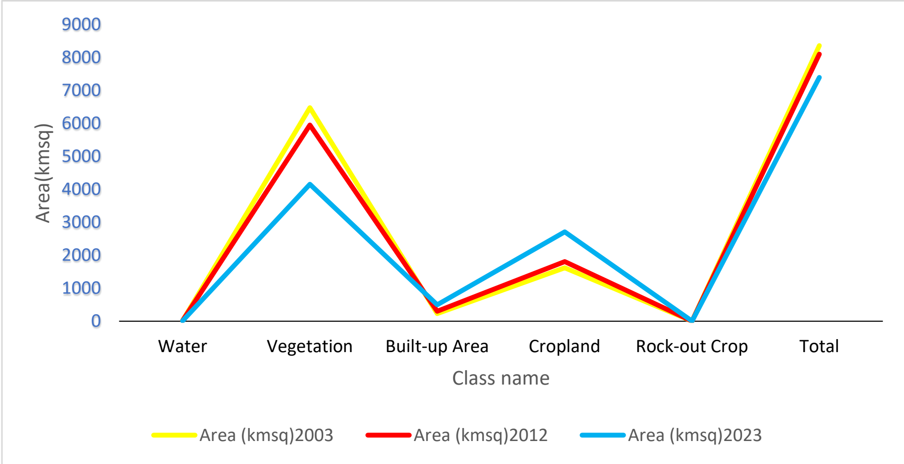

Figure 18. *Graph of 2003, 2012 and 2023 Land Use and Land Cover Classification.*

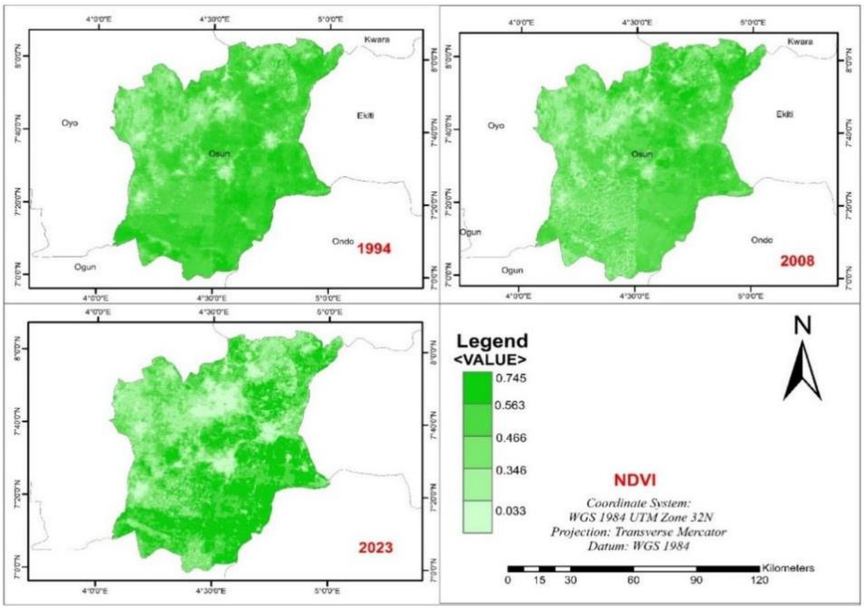

Figure 19. *Normalised Difference Vegetation Index (1994-2023).*

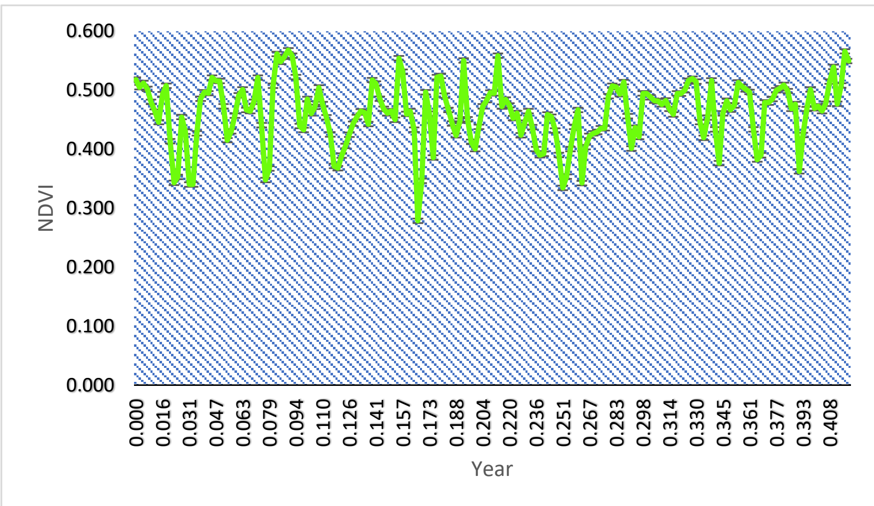

Figure 20. *Graph of Normalized Difference Vegetation Index (1994-2023).*

3.2.2. Carbon Stock

The carbon stock results are consistent with the observed decline in vegetation. Figures 21-26 show the distribution of carbon stock biomass for 2003, 2012, and 2023, while Figure 27 illustrates the temporal trend and Figure 28 identifies hotspot areas. Although the paper currently presents these mostly as maps and graphs, the interpretation is clear: where vegetation has been reduced, carbon storage potential has also declined. This is expected, since land-based carbon sinks become less effective when forests and other vegetated covers are degraded or converted. At a broader scale, the IPCC has noted that land and ocean carbon sinks become less effective with continued warming, and that conservation, improved management, and restoration of forests and other ecosystems remain among the most important land-based mitigation options.

For Osun State, the carbon stock hotspot map in Figure 28 is especially useful for planning because it helps identify locations where degradation and climate vulnerability are likely to coincide. These areas should be prioritised for restoration, afforestation, reforestation, and stricter land management, since they represent landscapes where ecological recovery could provide both mitigation and adaptation benefits.

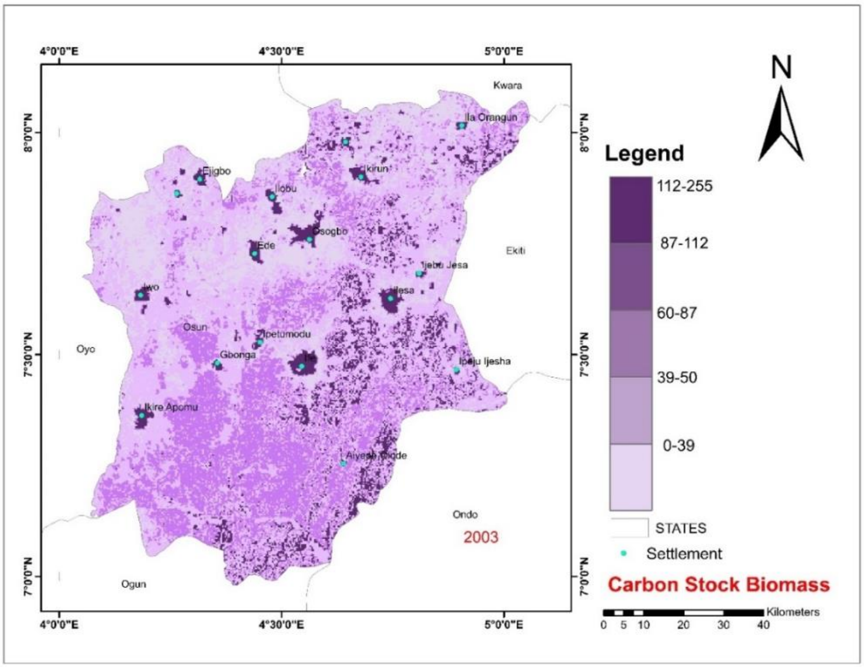

Figure 21. *Map showing Carbon Stock Biomass in 2003.*

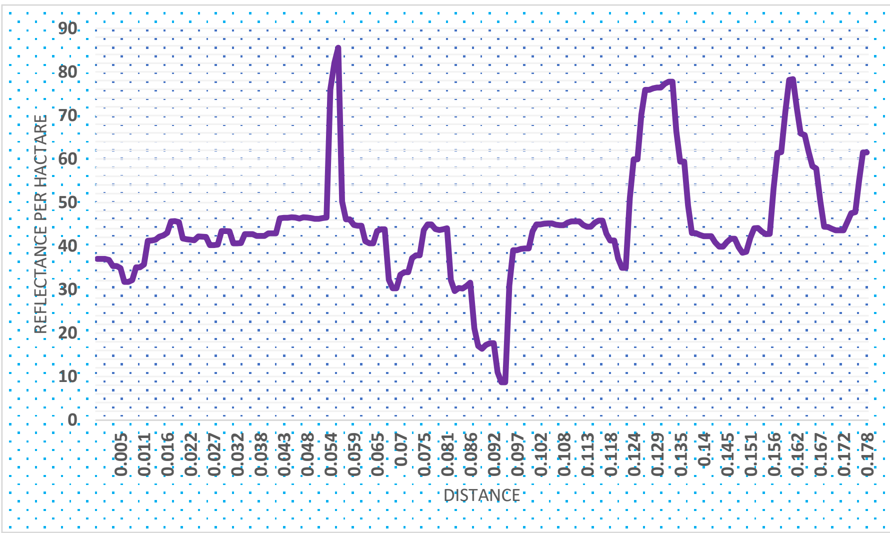

Figure 22. *Graph showing Carbon Stock Biomass in 2003.*

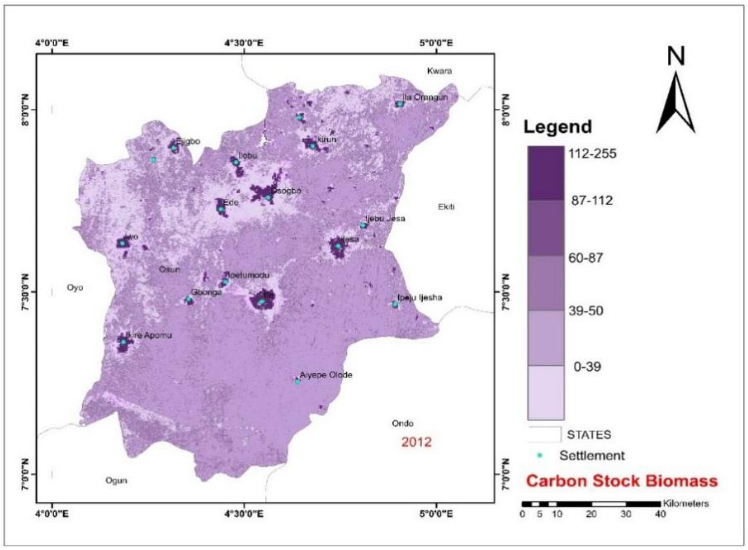

Figure 23. Map showing Carbon Stock Biomass in 2012.

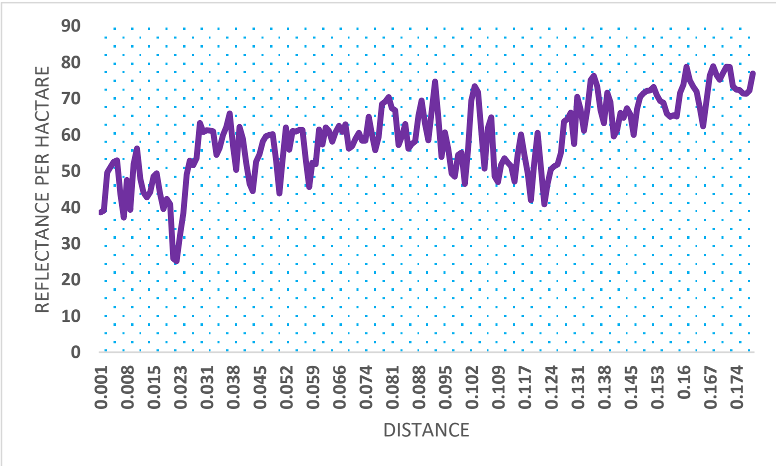

Figure 24. Graph showing Carbon Stock Biomass in 2012.

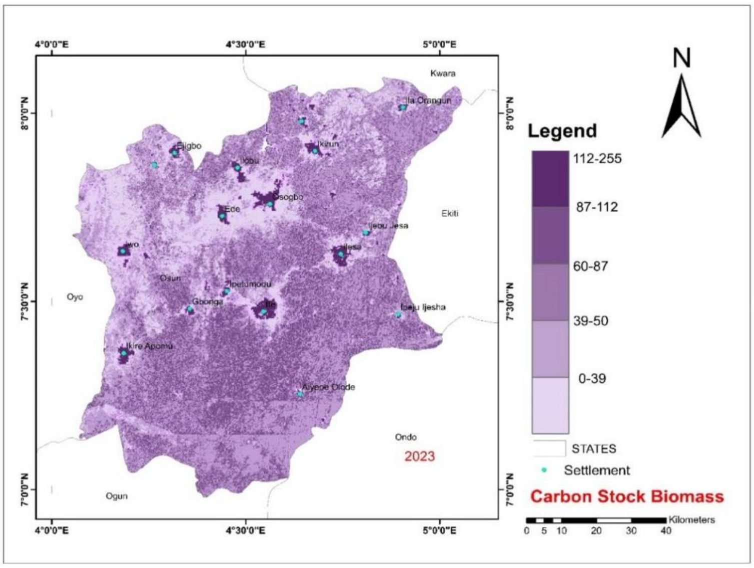

Figure 25. Map showing Carbon Stock Biomass in 2023.

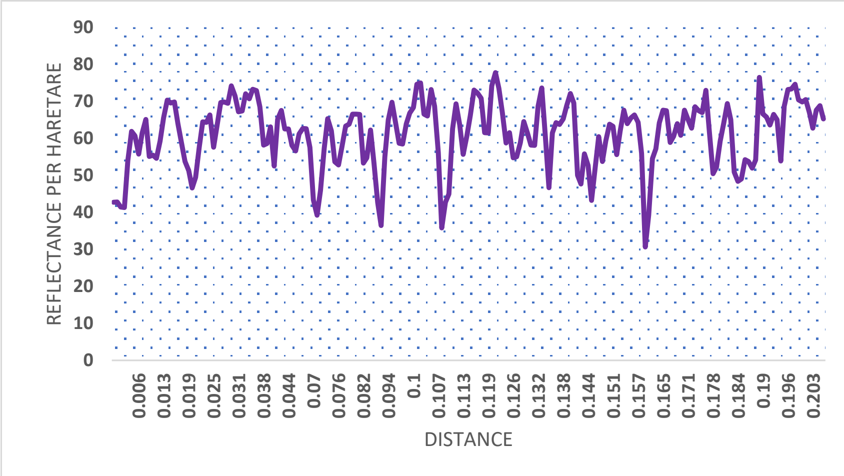

Figure 26. Graph showing Carbon Stock Biomass in 2023.

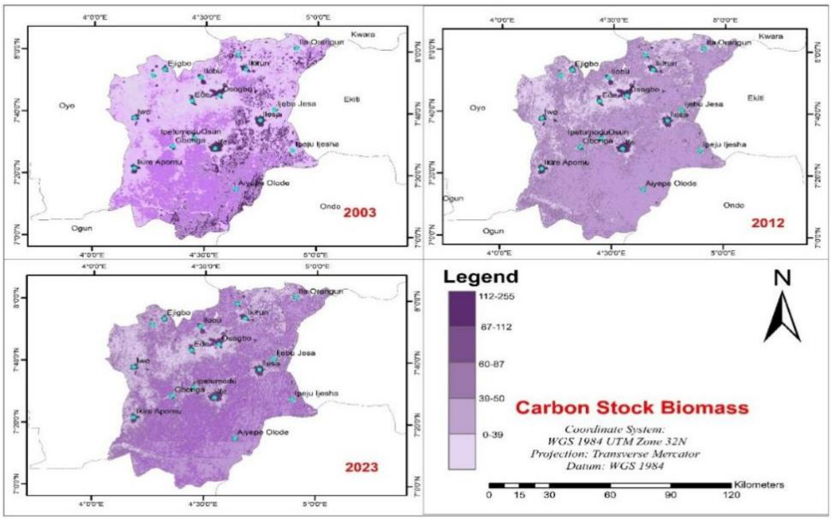

Figure 27. Map showing trend of Carbon Stock Biomass (2003-2023).

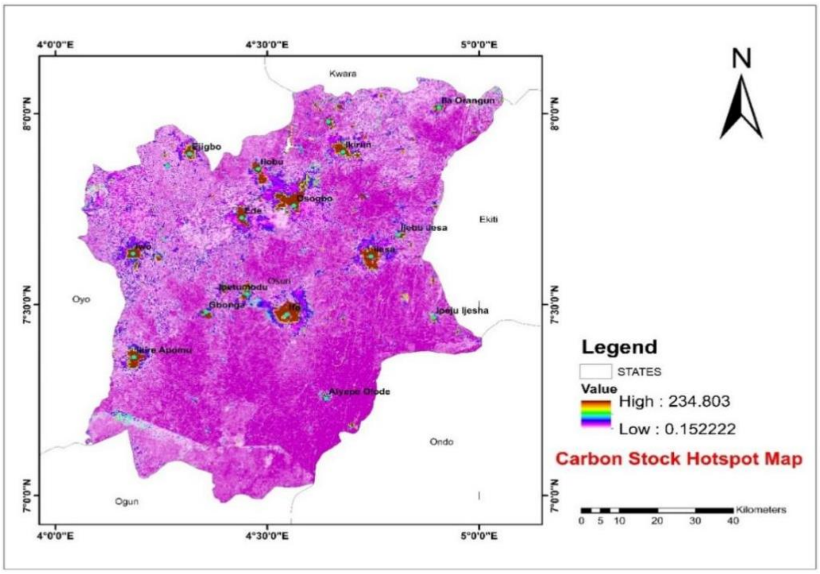

Figure 28. Map showing Carbon Stock Hotspot Area.

3.3. Dynamics of Land Use and Land Cover (2003–2023): Implications for Mitigation and Adaptation

The combined land use analysis in Table 10, Figure 29, and Figure 30 shows a broad restructuring of the Osun State landscape over the last two decades. Vegetation reduced by more than 2,300 km², while cropland expanded by over 1,000 km² and built-up land more than doubled. By contrast, water bodies and rock outcrops remained relatively stable. This indicates that the major transformation is taking place within the vegetation–cropland–urban interface, which is precisely where climate vulnerability is likely to intensify most rapidly.

These findings have direct implications for both mitigation and adaptation. From a mitigation perspective, the study supports reforestation, afforestation, ecosystem restoration, agroforestry, soil carbon management, and reduced conversion of forests and other ecosystems as appropriate land-based responses. These options are widely recognized as important climate mitigation measures and can also generate co-benefits for biodiversity, ecosystem services, and livelihoods.

From an adaptation perspective, the results suggest that responses should be spatially targeted. Areas with persistent NDVI decline and vegetation loss, as indicated in Figures 19 and 20, should be prioritized for restoration and sustainable land management. Agricultural zones should adopt climate-smart agriculture, including improved cropland management, agroforestry, moisture conservation, and water management. The FAO describes climate-smart agriculture as an approach that seeks to increase productivity, strengthen adaptation, and reduce greenhouse gas emissions where possible.

Urbanizing areas, especially those associated with rising built-up land in Tables 7-10 and Figure 30, require climate-resilient planning. This should include green infrastructure, improved drainage, flood retention measures, and protection of natural drainage corridors. The wider literature shows that urban greening provides local cooling, while natural river systems, wetlands, and upstream forests can reduce flood risk by storing water and slowing runoff. These measures are therefore particularly relevant to Osun State, where rising rainfall variability and expanding built-up areas may increase exposure to flood and heat stress.

Overall, the results support an integrated policy approach rather than separate treatment of mitigation and adaptation. In Osun State, land restoration, agroforestry, watershed protection, and urban greening are not only environmental measures; they are also practical climate responses that can help reduce vulnerability while preserving the land's carbon storage function. The central message from Figures 18, 27, 28, 29, and 30 is that continued land conversion without ecological safeguards will likely deepen climate risk, whereas coordinated land management can produce resilience and sustainability gains across multiple sectors.

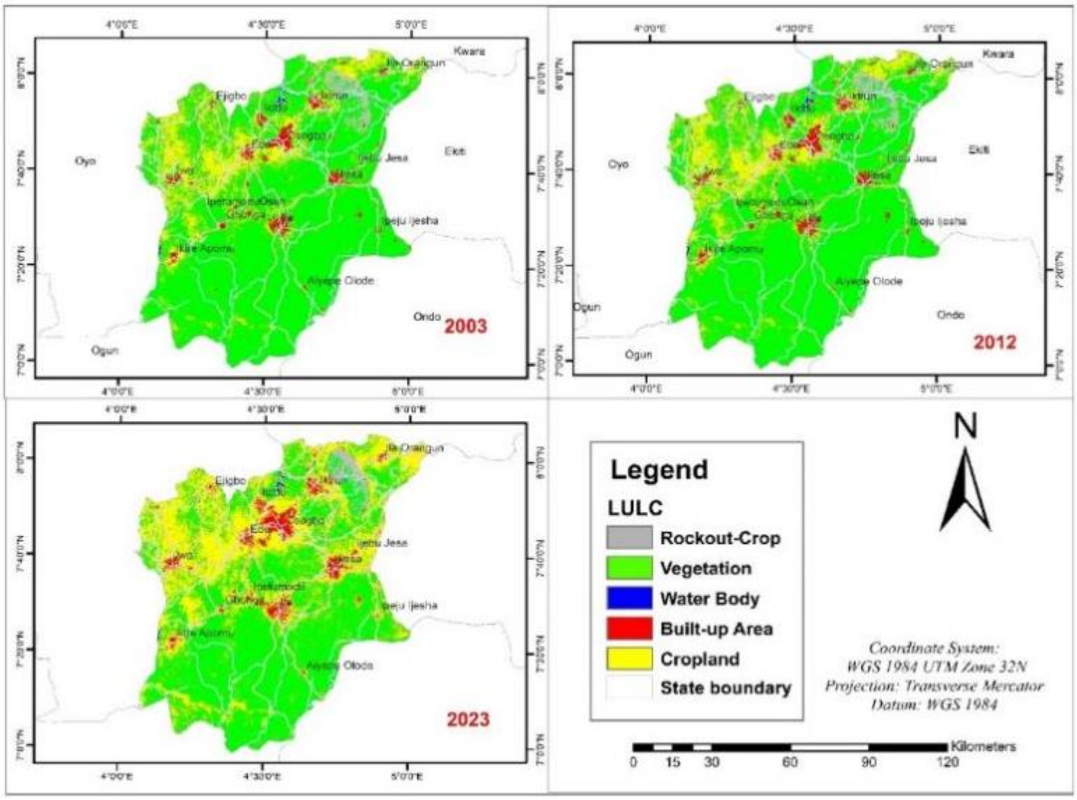

Figure 29. *Map showing Land Use and Land Cover Trend (2003-2023).*

Table 10. *Land Use and Land Cover Area (2003 -2023).*

Class	**Area (km^2) 2003**	**Area (km^2) 2012**	**Area (km^2) 2023**
Water	20.20	19.65	17.94
Vegetation	6476.3	5954.20	4154.20
Built-up Area	233.65	304.54	504.54
Cropland	1621.79	1813.32	2713.32
Rock-out Crop	7.45	7.10	6.89
Total	8359.385	8098.81	7396.89

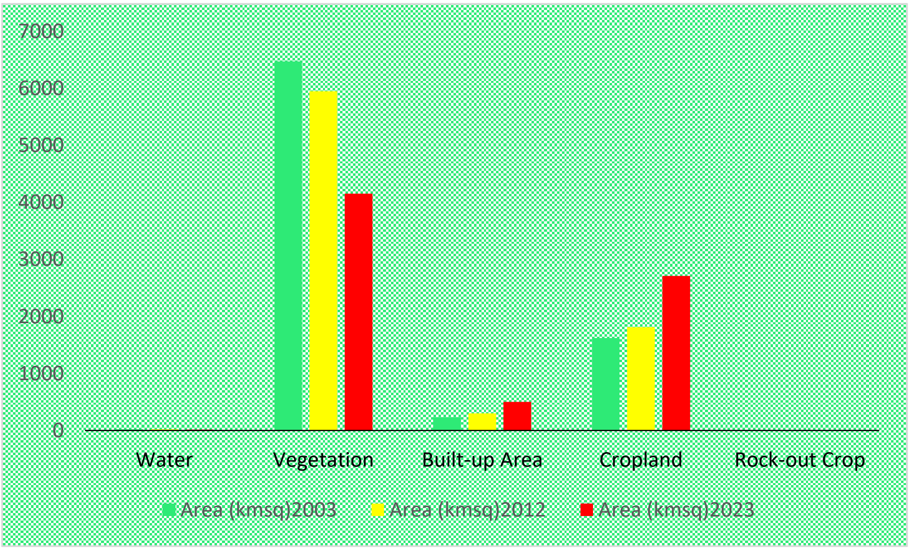

Figure 30. *Multiple Bar Chart showing Land Use and Land Cover Trend (2003-2023).*

4. Conclusion and Recommendations

This study shows that climate change in Osun State is occurring alongside significant land transformation, with important consequences for environmental sustainability and human livelihoods. The results indicate a gradual warming trend, increasing rainfall variability, rising humidity, and a general decline in wind speed, all of which point to growing climate instability. At the same time, land use analysis revealed a marked decline in vegetation cover from 77.50% in 2003 to 56.16% in 2023, accompanied by an increase in cropland from 19.40% to 36.68% and built-up area from 2.80% to 6.82%. These changes, together with the observed decline in NDVI and carbon stock, suggest that climate risk in Osun State is being intensified not only by changing atmospheric conditions, but also by unsustainable land conversion and ecosystem degradation.

The findings therefore highlight the need for integrated mitigation and adaptation measures centered on sustainable land management. Priority actions should include restoration of degraded vegetated areas, promotion of climate-smart agriculture, improved flood control and drainage infrastructure, and stronger land use planning to manage urban expansion. Areas showing the greatest vegetation and carbon stock loss should be prioritized for intervention, while routine geospatial monitoring should be strengthened to support evidence-based climate planning. Overall, improving resilience in Osun State will depend on linking ecosystem protection, agricultural sustainability, and climate-responsive development within a coordinated policy framework.

Abbreviations

CO_2	Carbon Dioxide
CH_4	Methane
GHGs	Greenhouse Gases
N_2O	Nitrogen Oxide
℃	Degrees Centigrade
PPM	Parts per Million
PPB	Parts per Billion

$GtCO_2$	Gigatonnes of Carbon Dioxide
DGVM	Dynamic Global Vegetation Models
NEP	Net Ecosystem Production
MERRA	Modern-era Retrospective Analysis for Research and Applications, Version 2
NASA	National Aeronautics and Space Administration
USGS	United States Geological Survey
UNWCMC	United Nations World Conservation Monitoring Centre
NDVI	Normalized Difference Vegetation Index
NIR	Near Infra-Red

Author Contributions

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Seyi Festus Olatoyinbo: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing

Samson Akintunde Ogunyemi: Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – original draft

Samuel Samson: Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing – original draft

Adebayo Gbenga Ojo: Data curation, Investigation, Validation

Babatunde Olaleye Salu: Data curation, Investigation, Validation

Matthew Olumide Adepoju: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing

Godstime Kadiri James: Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing

Raphael Ike Ndukwu: Data curation, Investigation, Validation

Conflicts of Interest

The authors declare no conflicts of interest.

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