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Spatiotemporal Assessment of Landsat derived Normalized Difference Vegetation Index (NDVI) for Forest degradation in Afaka Forest Reserve, Kaduna Nigeria.

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abstract

Urbanization and agricultural intensification, driven by population growth and lacking adequate management have heightened forest degradation risks. This study aims to assess spatio-temporal Landsat-derived Normalized Difference Vegetation Index (NDVI) for vegetation degradation. Supervised classification was used for NDVI analysis of Landsat imagery from 1986, 1999, and 2018 for Afaka Forest Reserve, with a 30 m resolution using Erdas Imagine 9.2. The results show the vegetation cover decreased by -3.83% from 1986 to 1999, but slightly increased by 1.69% from 1999 to 2018. The water body class decreased by -0.71% from 1986 to 1999 and slightly increased by 0.04% from 1999 to 2018. Overall, the non-vegetation cover increased by 0.14%, while vegetation and water bodies decreased by -0.11% and -0.04%, respectively. The relationship between climate characteristics and mean NDVI values shows a positive correlation (0.77), implying a direct impact of climate on forest cover. The decrease in vegetation cover and water bodies indicates a decline in forest resources, while the increase in non-vegetation class suggests the expansion of built-up areas, light forests, and bare surfaces. These changes provide clear evidence of vegetation degradation attributable to anthropogenic factors as well as natural factors (climate change). The study recommends a forest ecosystem restoration approach through forest governance and strengthened enforcement of strict conservation measures, adopting climate-adaptive and community-based forest management for sustainability.

1. Introduction

Forests play a significant role in maintaining ecological balance, sustaining the natural environment, and preserving biodiversity, all of which are crucial for human life and livelihoods (FAO, 2020). Globally, regions in the Global South are experiencing declines in urban vegetation cover, with decreases in vegetation health and density linked to rising land surface temperatures (Ullah et al., 2023). Several studies have attributed global environmental change to both human activity and climate variability (Cowie et al., 2018). However, the collective impact of human-induced drivers on savannah degradation is more complex and manageable than the impact of climate (Zhu et al., 2016). The continuous increase in human population has significantly impacted land use and land cover (LULC) due to the need to provide food, shelter, and housing for the growing population (Food and Agriculture Organization - FAO, 2020). Population growth has led to extensive changes in forest cover due to human activities such as fuelwood harvesting, bush burning, shifting cultivation, industrialization, infrastructural development, and urbanization in Nigeria (Federal Government of Nigeria, 2018).

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Since LULC investigations can significantly influence natural resource management, it is essential to have accurate and comprehensive data regarding LULC to assess changes in social, economic, and environmental factors for sustainability (Chaudhary & Pandey, 2019; Athick et al., 2019). These LULC changes are associated with significant alterations in albedo, accelerated rates of soil degradation, and biodiversity loss, exacerbating climate change (Li et al., 2021). Land use and land cover changes resulting from urbanization and the increasing anthropogenic activities are the primary causes of soil quality deterioration worldwide (Li et al., 2021). Monitoring ecological changes and managing natural resources require research that considers LULC changes (Ali et al., 2018). Alterations in forest cover exacerbate climate change threats because changes in forest structure, composition, and density determine whether a forest landscape acts as a carbon source or sink (Jibrin et al., 2018; Olsson et al., 2019; Adeyemi & Ayinde, 2022).

Climate change is a key indicator of environmental resource alteration (Chi et al., 2020), influencing physical, chemical, and biological processes at the Earth's surface-atmosphere interface. It significantly affects vegetation conditions and soil moisture levels (Urqueta et al., 2018). Land surface temperatures have been linked to increased water consumption, higher energy usage, and shifts in species composition and distribution, thereby impacting ecosystem functions (Zhou et al., 2017). In Kaduna Metropolis, studies have observed rising surface temperatures due to urban expansion and renewal projects, which have led to increased impervious surfaces and reduced vegetation cover (Zaharaddeen et al., 2016).

An analysis of MODIS NDVI and LST time-series data in Kaduna revealed a significant decline in vegetation and established a strong negative correlation between daytime LST and NDVI (Abubakar et al., 2024). Currently, there is no consistent account of the spatio-temporal, long-term trends of biomass loss caused by human activity and climate variability in Nigeria. This gap hinders critical efforts for ecosystem and environmental management. A review of existing literature reveals limited studies on NDVI changes in Afaka Forest, highlighting the need for further research to provide data for sustainable monitoring of vegetation cover changes. This study seeks to answer the following research questions: (i) What are the spatio-temporal Landsat-derived NDVI index of Afaka Forest Reserve from 1986 to 2018? (ii) What are the drivers of the forest degradation? and finally (iii) What are the relationship between climate and forest degradation? This study aims to assess spatio-temporal Landsat-derived NDVI for vegetation degradation in Afaka Forest Reserve, Kaduna State, Nigeria.

Materials and Methods

Study Area

Afaka Forest Reserve is located in Kaduna State, Nigeria, between latitude of 10°36'22"N to 10°37'12"N and longitude of 7°14'10"E to 7°17'0"E (Figure 1). The reserve covers a land area of 10,927 hectares and features as savanna vegetation type (Abaje et al., 2016). Afaka Forest experiences distinct dry and wet seasons, with the dry season occurring from November to March and the wet season from April to October. The mean annual rainfall is 1,032 mm, and temperatures range from 22°C at night to over 38°C during the daytime. Relative humidity varies between 15% during the dry season and 60% during the rainy season. The area falls within the high plains of Northern Nigeria and is characterized by inselbergs and a pediment landscape overlying a basement complex (Abaje et al., 2016).

Remotely Sensed and Climatic Data

The spatial data used in this study consist of Landsat imagery obtained from the United States Geological Survey (USGS) repository website for the period from 1986 to 2018, as shown in Table 1. These images were used to evaluate forest degradation over the study period. Landsat imagery is characterized by high temporal resolution and is easily accessible for satellite imagery analysis. Climatic data for the period from 1986 to 2015 were obtained from the Nigerian Meteorological Agency (NiMet). Other secondary data sources included data from sources including academic texts, peer-reviewed journals, and online materials.

Table 1. Imageries Description

Type	Date	Resolution (m)	Source	Level of Processing (L)
Landsat 5 TM	08 Jan, 1986	30	USGS	Collection 2 Level 2
Landsat 5 TM	28 Jan, 1999	30	USGS	Collection 2 Level 2
Landsat 8 OLI	16 Jan, 2018	30	USGS	Collection 2 Level 2

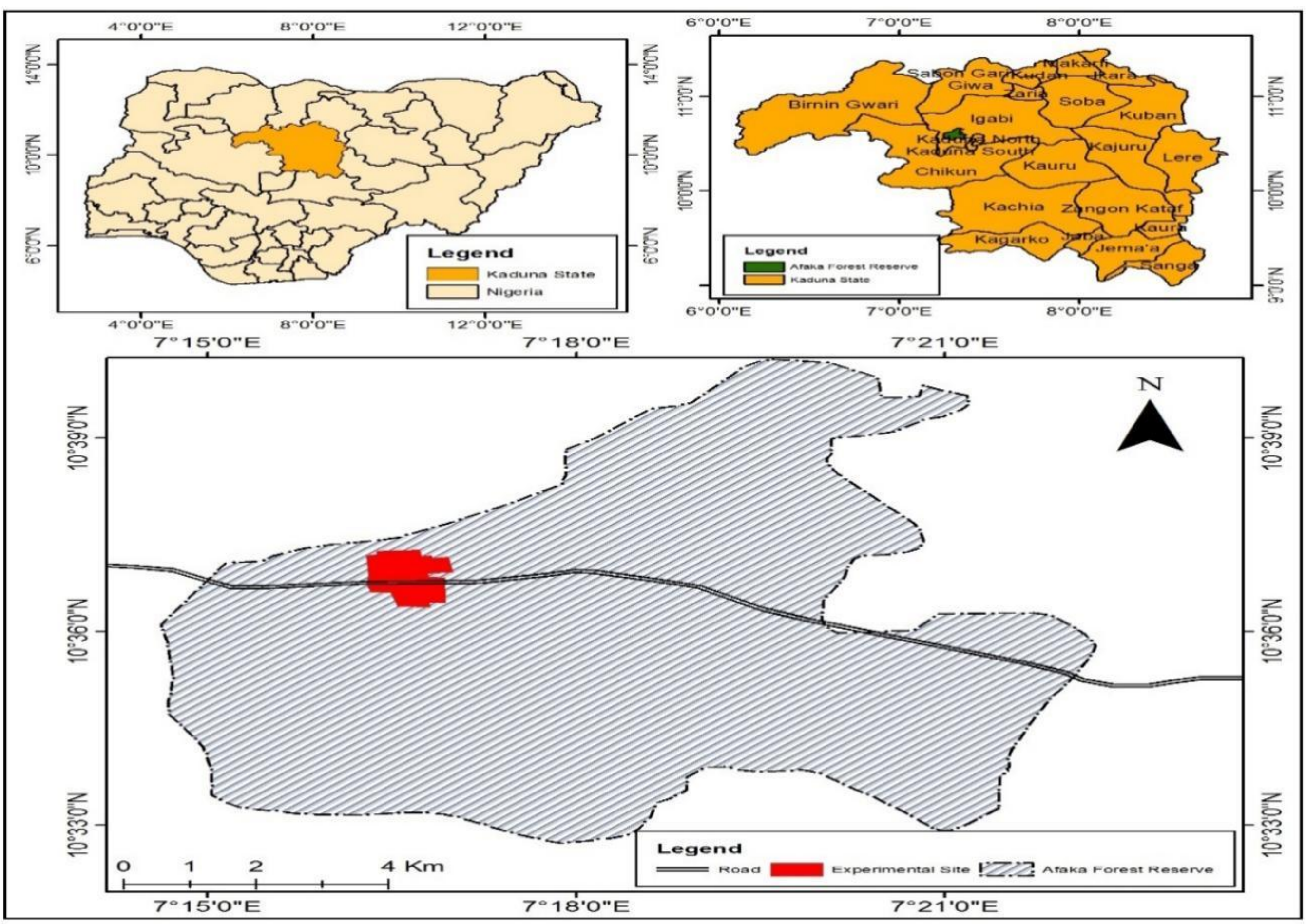

Figure 1: Nigeria, showing Kaduna, Afaka Forest Reserve.

Rainfall and Temperature Variation in Afaka Forest.

The monthly and annual variations in rainfall and temperature over Kaduna State are presented in Figures (2a) and (2b). It is shown in Figure (2a) that the rainy season lasts from April to October (seven months), while the dry season extends from November to March (five months), which is characteristic of the savanna region. Rainfall peaks in August, while the lowest rainfall occurs in March and November. Temperatures remain relatively uniform throughout the year, with the highest temperatures recorded in March and April, and the lowest in December and January. Figure (2b) illustrates rainfall and temperature variations over Kaduna, indicating an increasing trend from 1986 to 2015 for both climatic parameters. Rainfall variability (18%) was significantly higher than temperature variation (1.0%). The highest rainfall levels were observed in 1991 and 2015, which coincided with periods of high temperatures. Conversely, in 2001 and 2006, higher temperatures corresponded to lower rainfall. The greater variation in rainfall is likely to impact forest biodiversity, as rainfall is a key factor in forest growth and development.

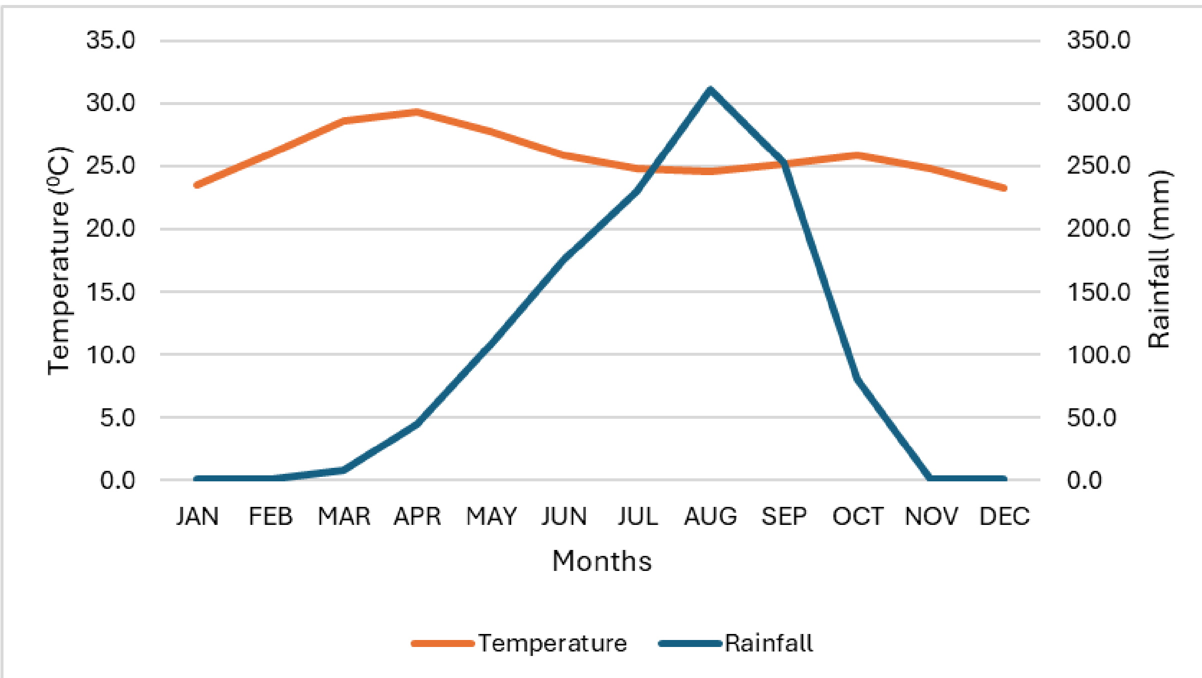

Figure 2a: Monthly Rainfall and Temperature variation in Kaduna over the study period.

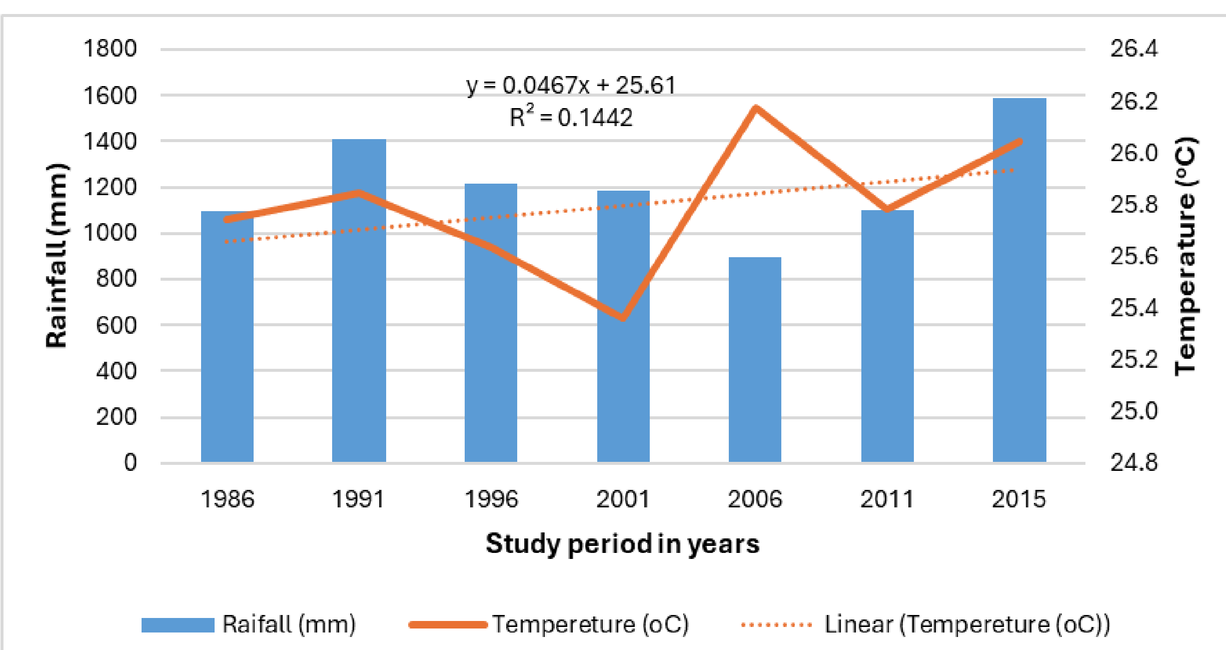

Figure 2b: Annual Rainfall and Temperature variation in Kaduna over the study period.

Methods of Data Processing
The processing of remotely sensed data was conducted in four steps: Preprocessing, NDVI Calculation (Normalized Difference Vegetation Index), NDVI Classification, and Spatio-temporal Analysis.

Preprocessing of Remotely Sensed Data
Preprocessing of Landsat images, specifically using Collection 2 Level 2 (L2) data, involved several steps to ensure the accuracy and consistency of the dataset. Landsat imagery for the years 1986, 1999, and 2018 was obtained from the USGS Earth Explorer and Landsat Level-2 Data Product distribution platforms. Radiometric corrections were applied to normalize pixel values, accounting for differences in sensor sensitivity and atmospheric conditions. Geometric corrections were performed to eliminate distortions caused by sensor movement, satellite motion, and Earth's topography. Finally, the preprocessed Landsat images were exported and saved in a suitable format, such as GeoTIFF, for further analysis.

Normalized difference vegetation index (NDVI) calculation
The NDVI is a widely accepted index for observing global vegetation and is particularly useful for monitoring changes in vegetation density and photosynthetic activity at regional and global scales. Given its effectiveness, NDVI was used in this study to analyze vegetation cover changes over the periods of 1986, 1999, and 2018.
NDVI = (NIR – VIS) / (NIR + VIS) ……………. …………equation 1
Where:
NDVI = Normalized Difference Vegetation Index
NIR = Near-Infrared Radiation
VIS = Visible Radiation/Red band
The NDVI values ranged from -1 to +1, where values close to 1 indicated dense vegetation, values around 0 or slightly above represented sparse vegetation or bare soil, and negative values corresponded to non-vegetative surfaces. It is important to note that different Landsat satellites utilized varying spectral bands to capture Near-Infrared (NIR) and Visible (Red) radiation. Specifically, the **Landsat 5** sensor captured NIR in **Band 4** and Visible (Red) in **Band 3**, whereas the Landsat 8 Operational Land Imager (OLI) sensor captured NIR in **Band 5** and Visible (Red) in **Band 4** (Jhon et al., 2016).

Classification of NDVI into Vegetation Cover Classes
The NDVI images were classified into vegetation cover classes using the NDVI threshold provided in **Table 2.** This classification process involved assigning specific vegetation cover categories to pixel ranges within the NDVI image based on their corresponding values. The primary objective was to identify and monitor changes in vegetation cover over time. The classifier employed was the maximum likelihood method. The kappa coefficient expresses proportionate reduction in error generated by a classification process compared with the error of a completely random classification. The kappa coefficient value represents how well remotely sensed classification agrees or is accurate to the referenced data (Jensen, 2005).

Cover Class	NDVI Range
Waterbody	Less than 0
Non-Vegetation/Bare Land	0 to 0.1
Sparse Vegetation	0.1 to 0.5
Dense Vegetation	0.5 above

Source: Bisrat & Berhanu (2018).

Spatio-temporal analysis
The spatial and temporal analysis of forest cover changes was conducted to identify patterns of vegetation dynamics across the study area from 1986 to 2018. This analysis aimed to detect spatial variations in forest cover and understand how these patterns evolved. To achieve this, **ArcGIS 10.8 Overlay tools** were employed, enabling the integration and comparison of NDVI-derived vegetation cover maps for different years (Esri, 2020).

RESULT
Spatio-temporal Variation of NDVI Density Map in Afaka
The NDVI density map of Afaka Forest for 1986, 1999, and 2018 (Figure 3) provides crucial insights into the vegetation conditions of the forest. The results indicate that the NDVI values ranged from -0.001 to 0.320, implying that land cover varied from water bodies to non-vegetation and sparse vegetation (Figure 3a, 3b, 3c, Table 3). Over the three study periods (1986, 1999, and 2018), the non-vegetation class dominated the land cover. The analysis shows a decrease in maximum NDVI values from 0.320 in 1986 to 0.312 in 1999 and further to 0.275 in 2018. Similarly, the minimum NDVI values declined from 0.021 in 1986 to -0.019 in 1999 and -0.001 in 2018.
The trends in maximum and minimum NDVI values exhibit a consistent decline from 1986 to 2018. However, NDVI mean, range, and standard deviation values increased from 1986 to 1999, but subsequently, they declined from 1999 to 2018 (Table 3). Figure 4 illustrates the decrease in both maximum and minimum NDVI values, while mean NDVI values exhibit a general upward trend over the study period. These findings highlight the complex interactions between human interventions, natural factors, and vegetation dynamics in the Afaka Forest Reserve.

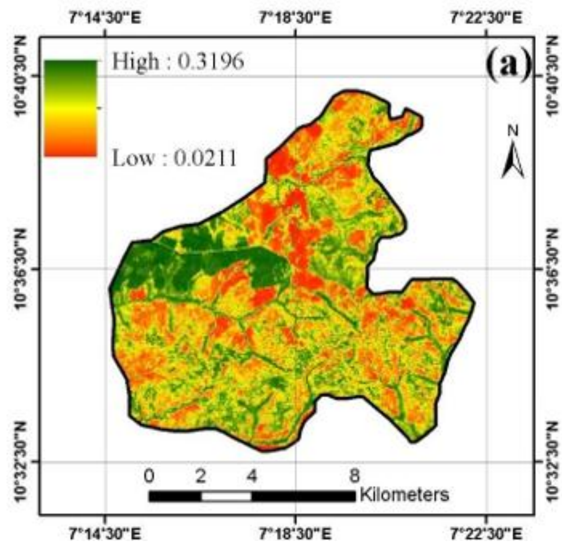

Figure 3a: NDVI density map of Afaka forest reserve for 1986

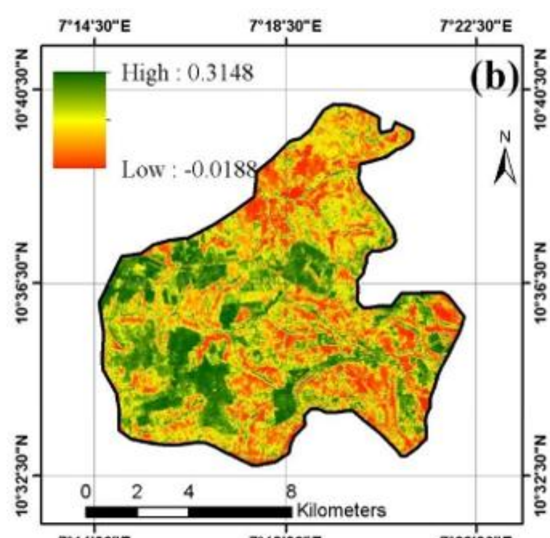

Figure 3b: NDVI density map of Afaka forest reserve for 1999

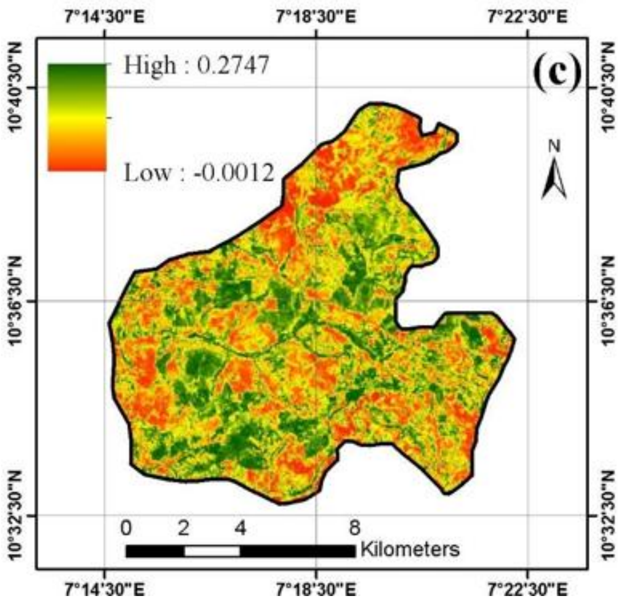

Figure 3c: NDVI density map of Afaka forest reserve for 2018

Table 3: NDVI Statistics over the study periods.

Year	MIN NDVI	MAX NDVI	RANGE NDVI	MEAN NDVI	STD NDVI
1986	0.021	0.320	0.299	0.116	0.031
1999	-0.019	0.315	0.334	0.144	0.034
2018	-0.001	0.275	0.276	0.143	0.025

Classified vegetation cover map according to NDVI threshold values

The classification of vegetation cover into distinct classes based on NDVI threshold values, as presented in Table 4 and Figures 4a and 4b, provides a comprehensive overview of land cover distribution within the Afaka Forest Reserve. The results indicate that the non-vegetation class (NDVI = 0 – 0.1) increased by **5.56%** from 1986 to 1999, followed by a slight decline of **-1.70%** from 1999 to 2018.

Similarly, the vegetation cover (NDVI > 0.1) exhibited a **-3.83%** decrease between 1986 and 1999, before experiencing a modest increase of **1.69%** from 1999 to 2018. Additionally, the water body class (NDVI < 0.0) declined by **-0.71%** from 1986 to 1999 but showed a minor increase of **0.04%** between 1999 and 2018.

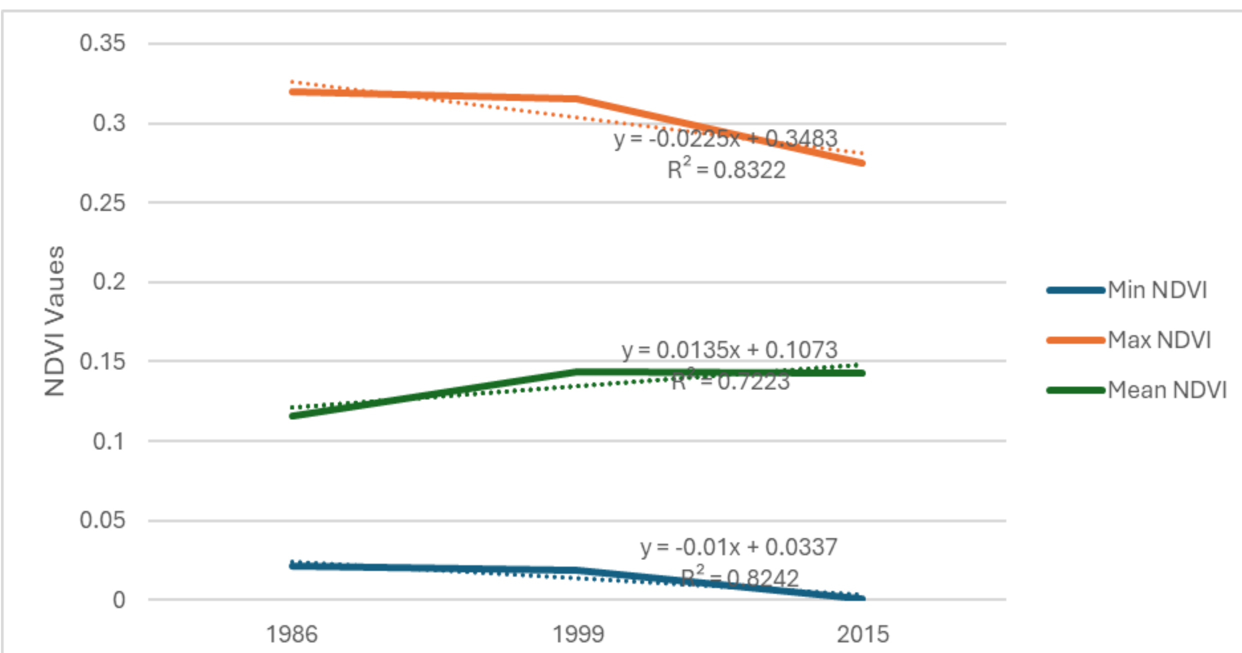

Figure 4a: Descriptive statistics of NDVI values in Afaka forest (1986-2015).

Table 4: Vegetation Cover classes From NDVI Threshold classification

class	1986 Area (km^2)	%	1999 Area (km^2)	%	2018 Area (km^2)	%
Non-Vegetation	65.91	58.42	71.05	62.98	69.13	61.28
Vegetation	46.08	40.85	41.76	37.02	43.67	38.71
Water	0.82	0.73	0.01	0.01	0.01	0.01
	112.81	100.00	112.81	100.00	112.81	100.00

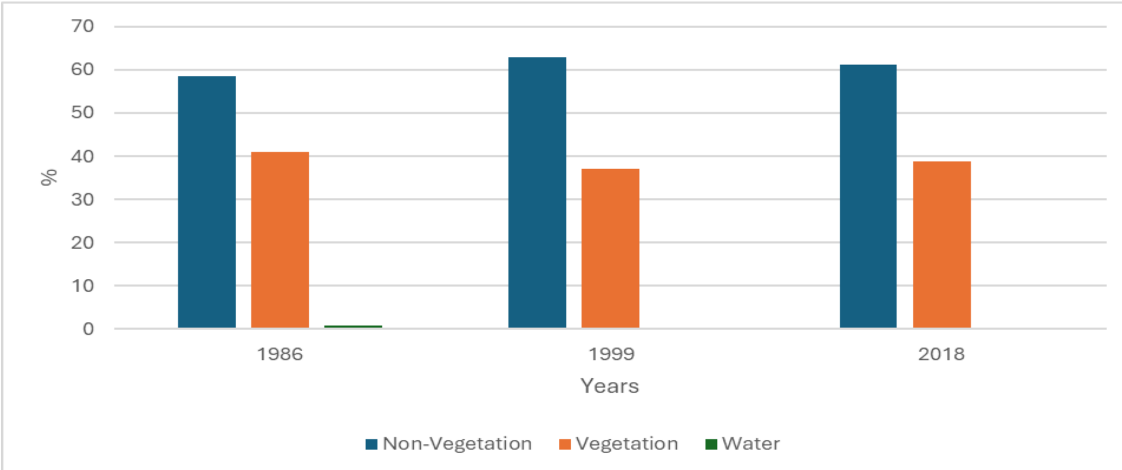

Figure 4b: Vegetation Cover Changes from NDVI Threshold Classification 1986 to 2018

Table 5: Vegetation Cover Changes 1986 to 2018

	1986 to 1999		1999 to 2018		Annual Rate	
	Area(km^2)	%	Area(km^2)	%	Area(km^2)	%
Non-Vegetation	5.14	4.56	-1.92	-1.70	0.10	0.14
Vegetation	-4.32	-3.83	1.91	1.69	-0.08	-0.11
Water	-0.81	-0.71	0.01	0.01	-0.03	-0.04
	0.00	0.00	0.00	0.00	0.00	0.00

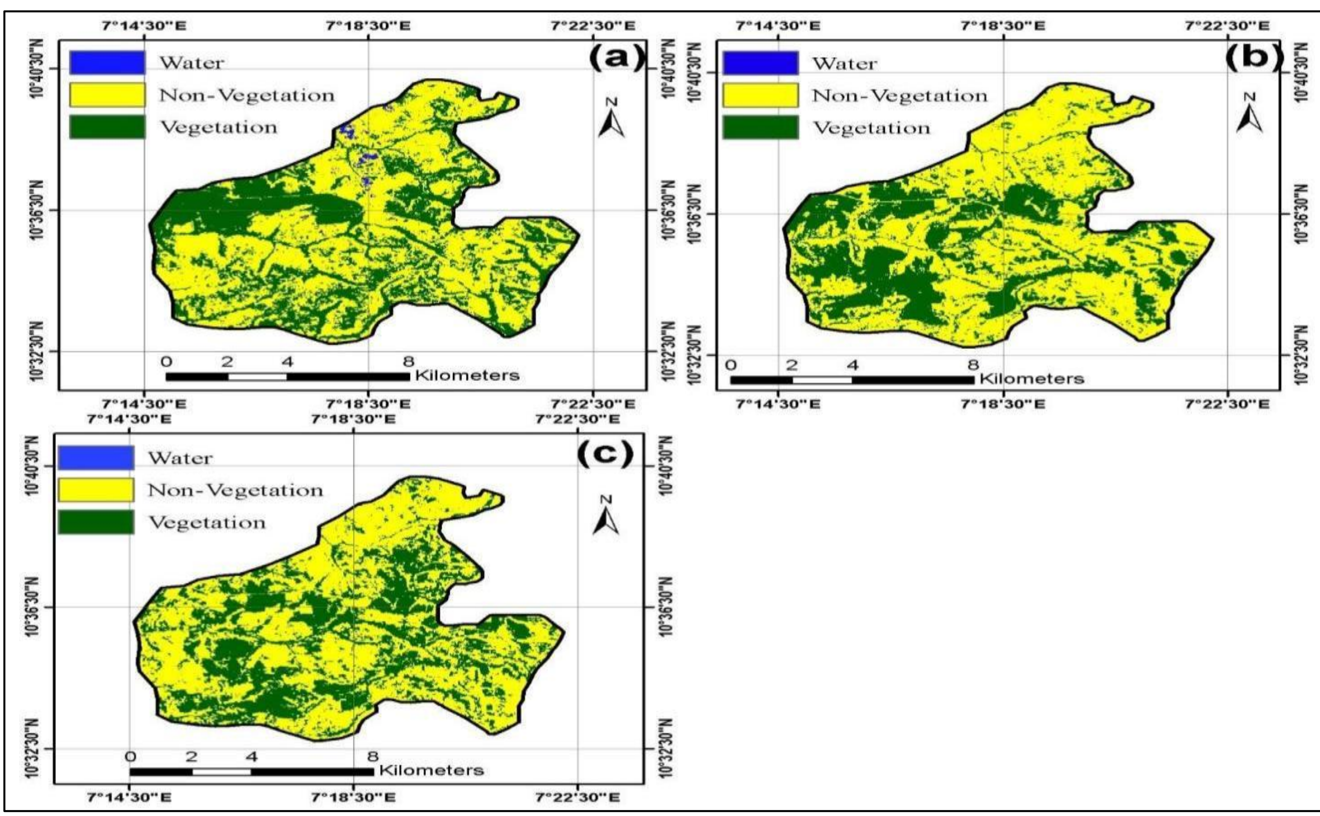

Figure 5: Land use land cover changes for (a) 1986, (b) 1999, and (c) 2018

Overall, the non-vegetation cover increased by **0.14%**, while forest cover and water surfaces declined by **-0.11%** and **-0.04%,** respectively. These percentages highlight the dominance of non-vegetation cover types, emphasizing potential areas of concern for conservation efforts.

The map analysis indicates that most of the forest degradation occurred between 1986 and 1999, followed by a period of partial recovery from 1999 to 2018. During the 1986–1999 period, a total of 5.14 km² of land cover was lost to non-vegetation, while only 0.10 km² was recovered between 1999 and 2018. Additionally, 4.32 km² of vegetation was converted to other land cover types between 1986 and 1999, whereas only 1.91 km² was restored to vegetation from other land cover types in the subsequent period. The rate of increase in non-vegetation areas was significantly higher than the rate of vegetation recovery, with the percentage of land lost to non-vegetation being 300% greater than the percentage gained in vegetation cover (Table 5).

Vegetation density (NDVI) transition matrix analysis of Afaka forest

The transition matrices, presented in Tables (6a) and (6b), offer a detailed analysis of the changes between different vegetation cover classes over specific periods. The transition matrix for 1986 to 1999 reveals that the non-vegetation class experienced a higher loss of 21.97 km² compared to a gain of 16.87 km². Conversely, the vegetation class recorded a higher gain of 21.20 km² than its loss of 16.92 km², indicating some level of forest recovery. Similarly, the water body category experienced a net gain, suggesting minor fluctuations in water coverage over time (Table 6a).

In contrast, the transition matrix for **1999 to 2018** shows that the non-vegetation class experienced a greater gain of **19.15 km²** compared to a loss of **17.27 km².** Conversely, the vegetation class recorded a higher loss of 19.16 km² than its gain of 17.16 km², indicating a net decline in vegetation cover. Similarly, the water body category experienced a net gain, suggesting fluctuations in water coverage. The land cover transition analysis, illustrated in Figure 6, provides a visual representation of the shifting land cover patterns over time, offering a comprehensive overview of landscape dynamics within the Afaka Forest Reserve. By comparing land cover distributions across different periods, the analysis highlights areas experiencing significant changes and helps identify potential drivers of land cover transformation.

Table 6a: Transition Matrix 1986 to 1999 in km^2

	Cover 1999				
Cover 1986	Non-Vegetation	Vegetation	Water	Total 1986	Gain
Non-Vegetation	49.04	16.87	0.00	65.91	16.87
Vegetation	21.20	24.83	0.00	46.03	21.20
Water	0.77	0.05	0.00	0.82	0.82
Total 1999	71.01	41.75	0.01	112.8	
Lost	21.97	16.92	0.01		

Table 6b: Transition Matrix 1999 to 2018 in km^2

	Cover 2018				
Cover 1999	Non-Vegetation	Vegetation	Water	Total 1999	Gain
Non-Vegetation	51.90	19.141	0.004	71.05	19.145
Vegetation	17.23	24.497	0.006	41.73	17.24
Water	0.004	0.02	0.002	0.026	0.024
Total 2018	69.14	43.66	0.012	112.8	
Lost	17.27	19.161	0.010		

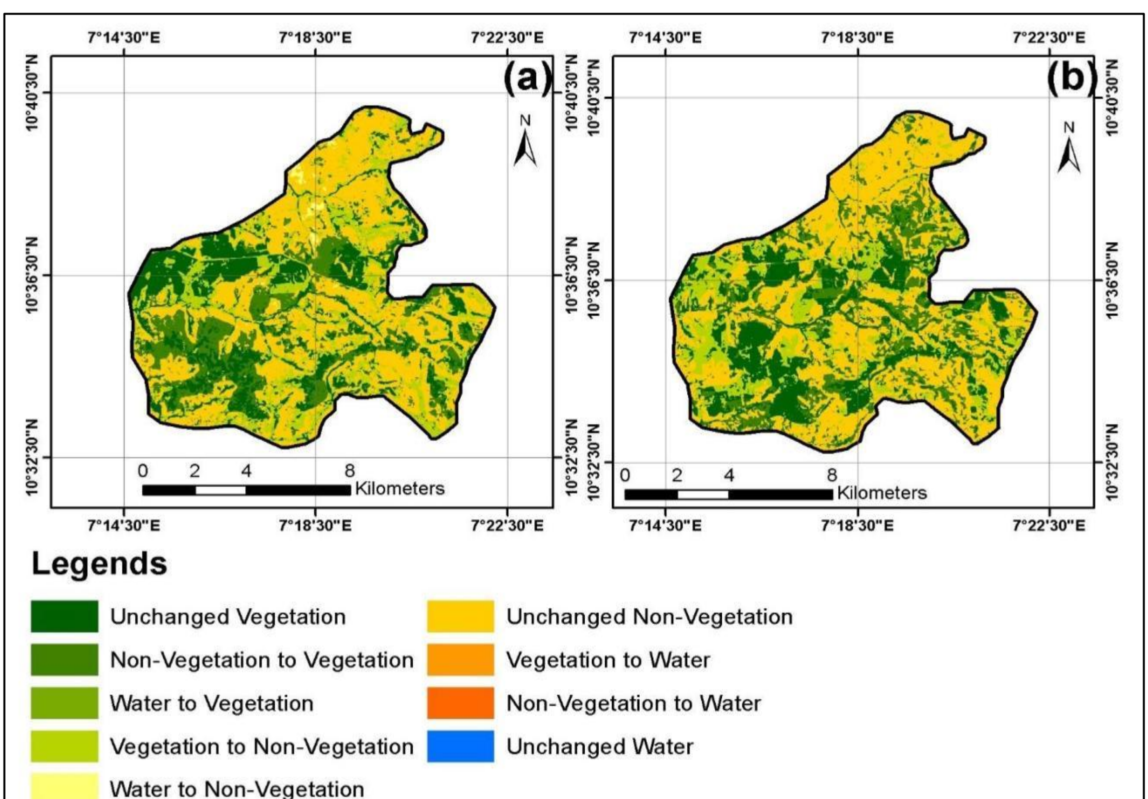

Figure 6: Landcover Transition (a) 1986 and 1999, (b) 1999 and 2018

Climate characteristics and forest cover changes.

The analysis of mean annual rainfall, mean daily temperature, maximum, minimum, and mean NDVI values is presented in Figures (7a) and (7b).

Figure (7a) presents an analysis of the variation between annual rainfall and maximum, minimum, and mean NDVI values. The results indicate that rainfall and mean NDVI values generally increased from 1986 to 2015, while maximum and minimum NDVI values showed a decreasing trend over the same period. Similarly, Figure (7b) illustrates the variation between mean temperature and NDVI values, revealing that mean daily temperature and mean NDVI values increased, whereas maximum and minimum NDVI values decreased throughout the study period. Statistical analysis (Table 7) indicates a significant positive correlation ($p < 0.05$, $r = 1.00$) between rainfall and temperature, suggesting that as rainfall increases, temperature also rises. Rainfall exhibited a negative correlation with minimum (-0.435) and maximum (-0.958) NDVI values, but a positive correlation with mean NDVI values (0.773). Similarly, temperature showed a negative correlation with minimum (-0.438) and maximum (-0.957) NDVI values, while displaying a strong positive correlation (0.776) with mean NDVI values. These findings suggest a direct relationship between climatic variables and maximum/minimum NDVI values, while also indicating a highly positive relationship between climatic factors and mean NDVI values. This underscores the influence of climate variability on vegetation cover changes, emphasizing the need for climate-adaptive conservation strategies.

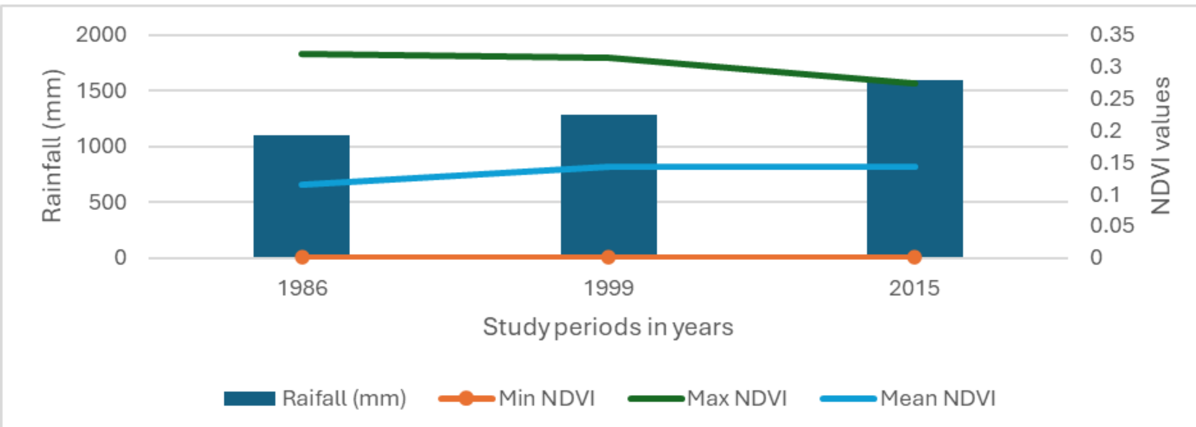

Figure 7a. Variation of the NDVI statistics and annual precipitation

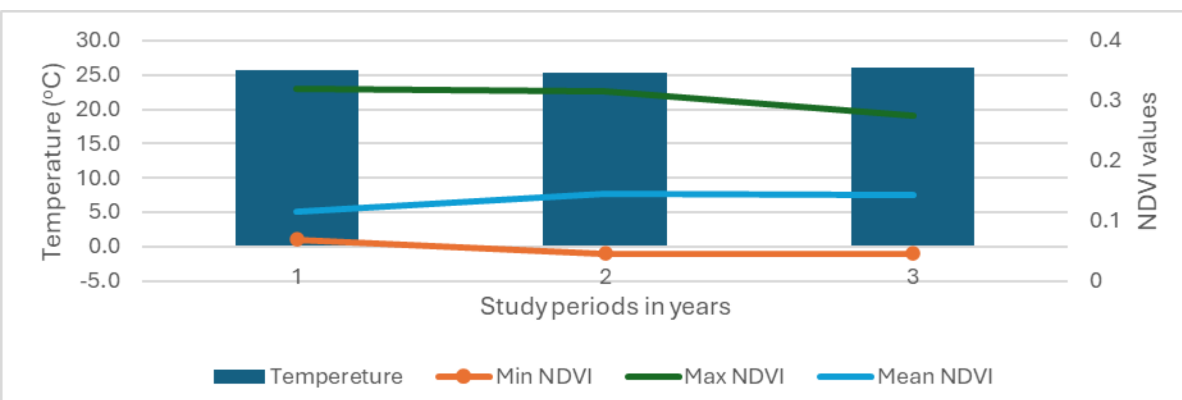

Figure 7b. Variation of the NDVI statistics and daily temperature

Table 7: Correlation analysis between Climate characteristics and NDVI in Afaka.

	Rainfall	Temperature	Min	Max	Mean
Rainfall	1				
Temperature	1.000**	1			
Min	-0.435	-0.438	1		
Max	-0.958	-0.957	0.159	1	
Mean	0.773	0.776	-0.907	-0.559	1

**. Correlation is significant at the 0.01 level (2-tailed).

Discussion

Land cover change analysis of Afaka forest

The decrease in vegetation cover from 1986 to 1999 can be attributed to illegal logging, fuelwood harvesting, and farming by local communities around Kaduna metropolis. In contrast, the increase in vegetation cover between 1999 and 2018 was likely due to afforestation projects, including the plantation of more tree species by the Afaka Forest Reserve Agency and continuous protection efforts. This aligns with the findings of Adenle et al. (2020), who reported improvements in vegetation cover across the Savannah region, attributing them to land management programs such as afforestation and reforestation with local tree species and drought-resistant shrubs.

Similar trends have been observed in previous studies. Adeyemi and Ibrahim (2020) and Olokeogun et al. (2021) reported that vegetation density is a response to both climatic and anthropogenic pressures. Rahayu et al. (2018) also found that high NDVI density values (indicating dense vegetation) declined in West Java Province, while low-density NDVI values increased, signifying land degradation. Kessy et al. (2016) identified forest fires as a major driver of forest degradation, a finding further supported by Amuyou et al. (2021), who documented human-induced forest fires as a leading cause of vegetation loss in REDD+ project communities in southeastern Nigeria. Similarly, Hu et al. (2023) observed a decline in vegetation cover and an increase in non-vegetation areas, largely due to increased farmland demand, urban expansion, and migration.

The increase in non-vegetation areas between 1986 and 1999 was largely due to deforestation, as the Afaka forest has been subjected to illegal timber harvesting and fuelwood extraction. Additionally, annual bushfires set by hunters have severely affected biodiversity, as depicted in Plates 1 and 2. These findings are in line with Mamun et al. (2022), who reported an increase in built-up areas and a decline in forested lands in Baroiyadhala National Park (1978–2019). The authors attributed the decrease in forest cover to anthropogenic activities, while the reduction in bare land resulted from afforestation programs. Likewise, Adewuyi and Olofin (2017) reported that 70% of forest cover in Kaduna had been converted to agricultural land, with an additional 10% transformed into waste dumps, roads, and bare land/water ponds—primarily driven by the increasing demand for fuelwood in Kaduna metropolis. Further supporting these observations, Rahayu et al. (2018) and Li et al. (2021) noted that large portions of forest areas have been converted to non-forest uses, while only minimal areas have transitioned from non-forest to forest. Similarly, Sulaiman et al. (2017) identified forest degradation due to bushfires caused by hunters and honey harvesters, poor grazing management, and fuelwood collection.

These findings highlight a continuous decline in forest cover over time, a trend consistent with reports from the Food and Agriculture Organization (FAO, 2020). The FAO further reported that 3.9 million hectares of African forests were lost between 2010 and 2020, a rise from the 3.4 million hectares lost between 2000 and 2010. Additionally, FAO (2015) documented persistent deforestation in Nigeria, noting that the country's tree cover declined from 17,234 ha in 1990 to just 9,041 ha in 2010. These trends underscore the urgent need for sustainable land management policies, afforestation initiatives, and stricter enforcement of forest conservation measures to mitigate the impact of deforestation and land degradation in Nigeria.

Vegetation density (NDVI) transition matrix analysis

The increase in non-vegetation areas and the loss of vegetation cover are clear indicators of forest degradation, leading to the conversion of forest land into farmlands, shrubs, and grasslands. These findings align with the reports of Sulaiman et al. (2017) and Li et al. (2021), who documented significant deforestation and vegetation loss in the Niger Delta, Kano, and Kedong forests. The primary causes of this degradation were unguided fuelwood extraction, logging, cultivation on steep slopes, and oil mining activities in the delta region. Despite government efforts in afforestation and reforestation, the overall forest cover in Afaka Forest has not changed significantly. The land cover transitions observed in the reserve can be attributed to a combination of natural factors (climate change) and anthropogenic activities, including continuous cultivation, fuelwood extraction, and overgrazing. These findings highlight the urgent need for sustainable land management policies and stricter enforcement of conservation measures to curb further forest degradation.

Climate characteristics and forest cover changes.

The Normalized Difference Vegetation Index (NDVI) is influenced by climate variations, where negative NDVI values during drought periods indicate degradation, while positive NDVI values in rainy years signal vegetation recovery (Ezaidi et al., 2022). The positive correlation between climatic variables and mean NDVI values in this study suggests a direct impact of climate on forest cover in Afaka Forest Reserve. Ibrahim et al. (2015) similarly reported a strong correlation between NDVI and rainfall in West African countries, while Yang et al. (2021) found a consistent upward trend in NDVI and climatic factors over 34 years (1982–2015) in the Hexi Corridor, China. However, the effects of climate change on vegetation degradation cannot be confirmed through field observations alone, as seasonal variations also impact forest cover (Sun and Qin, 2016). The negative correlation between climatic data and both maximum and minimum NDVI values in this study aligns with Abubakar et al. (2024), who reported a negative correlation between land surface temperature and NDVI values in Kaduna. This implies that forest degradation is not solely driven by climate change but is also influenced by human activities, including fuelwood collection, logging, and forest fires (Adenle et al., 2020). Moreover, Ezaidi et al. (2022) confirmed that lower NDVI values correspond to periods of higher temperatures, highlighting the combined effects of climate variability and anthropogenic activities on vegetation loss, estimated at 2,989.59 hectares. Earlier studies (Brandt et al., 2019; Adenle et al., 2020; Brandt et al., 2022) also documented the impact of human activities on forest cover in African nations, even in regions with favorable climatic conditions. Brandt et al. (2019) linked fuelwood extraction, farming, and overgrazing to vegetation degradation in the Sahel region, while Adenle et al. (2020) found that human activities contributed more to vegetation loss in tropical regions than climate factors. Additionally, Ademola and Bamigboye (2016) reported that an increase in mean annual temperature by 1.1°C (above the global mean of 0.74°C) and a decrease in mean annual rainfall by 81 mm were linked to forest degradation.

Policy Implication

i. Strengthened enforcement of forest reserve regulations such as penalties for illegal logging and regulate bush burning will reduce the continuous loss of vegetation cover and increase in non-vegetation cover, as there is weakness in forest protection enforcement.
ii. The need to institutionalize satellite-based monitoring systems for forest monitoring and urban expansion and land allocation planning around Kaduna environs, since NDVI have demonstrated sensitivity to climate and anthropogenic factors.
iii. Adoption of Climate Forest management system through planting drought resistance indigenous tree species to assist natural regeneration and monitoring seasonal fire control regulations aligned with climatic risk periods.
iv. Institutionalizations of community-based forest management systems through engaging communities around the forest to be involved in forest protection and provisions of alternative source of energy to discourage deforestation and provide incentives to those adopting agroforestry systems.

Socioeconomic Implication

i. Livelihood vulnerability: The decrease in vegetation cover will result to decrease in the number of grazing resources, fuelwood and other non-timber forest material in the area, and this will result in low-income generation for households who depend on the forest for livelihood.
ii. Urban Energy Pressure: The continuous increase in human population in the study area has resulted in an increase in the demand for fuelwood as their major source of fuel. There is thus, the need for an introduction of alternative source of fuel to reduce pressure on the forest.
iii. Ecosystem Service Loss: The continuous decrease in forest resource due to degradation will trigger the loss of soil fertility, drying up of water bodies and unfavorable climatic condition which will lead to flooding, heat stress and general economic loss in agriculture

Conclusion

The current study has utilized Landsat imagery with a 30m resolution, applying radiometric and geometric corrections to ensure consistency. This research enhances precision by employing supervised classification and statistical correlation analyses to link NDVI trends with environmental drivers. I showed that there was a significant decline in the vegetation cover in Afaka Forest Reserve from 1986 to 2018, with non-vegetation areas expanding due to anthropogenic activities and climate change. Climate variables, particularly rainfall and temperature, showed a positive correlation with the NDVI values, indicating their direct influence on vegetation health and density. Field observations confirmed that drivers of deforestation such as fuelwood collection, overgrazing, continuous cultivation, and forest fires have aggravated land degradation. Urgent conservation measures including afforestation, controlled logging, and community-based forest management are needed to restore and sustainably manage the reserve. The study's findings highlight the policy significance of NDVI-based land use planning. Integrating NDVI monitoring into environmental policies can support evidence-based decision-making, aiding deforestation mitigation and sustainable forestry. By pinpointing areas of significant vegetation loss, policymakers can implement targeted reforestation and afforestation efforts. NDVI analysis also strengthens early warning systems for land degradation, enabling timely interventions and adaptive land management. Incorporating remote sensing into national frameworks enhances forest conservation and climate resilience.

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Plate 1: Bush burning by hunters in Afaka Forest

Plate 2: Evidence of illegal lumbering by lumber in Afaka forest.