

Geospatial Assessment and Mapping of Degraded Areas in the Sudan Savannah of Nigeria Using GIS and Remote Sensing Techniques

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ABSTRACT

The Sudan Savannah Zone of Nigeria has experienced notable shifts in land productivity due to the combined impacts of anthropogenic activities and climatic factors. Identifying and mapping degraded areas is critical, particularly in this region characterized by rapid population growth and advancing desertification. This study employed MODIS satellite imagery to evaluate land degradation dynamics in Sokoto and Kebbi States within the Sudan Savannah Zone from 2001 to 2021, utilizing Normalized Difference Vegetation Index (NDVI) trend analysis and correlation methodologies. Findings revealed that 31.06% of the study area exhibited land degradation, while 23.41% demonstrated productivity enhancements. Spatial analysis highlighted an escalating trend of degradation in Kebbi State, in contrast to significant improvements observed in Sokoto State. Human activities, including overgrazing and unsustainable agricultural practices, emerged as predominant drivers of degradation, whereas land recovery initiatives and natural regeneration processes contributed to productivity gains. The results underscore the urgency of adopting integrated land-use planning strategies to harmonize food security objectives with environmental sustainability, thereby advancing Nigeria's efforts toward achieving land degradation neutrality.

Keywords: Land degradation; MODIS; NDVI; Nigeria; GEE

1.0 INTRODUCTION

UNESCO cautions that by 2050, up to 90% of the Earth's land surface may experience degradation, posing significant threats to biodiversity and human well-being (UNESCO, 2024). When land is degraded, soil carbon and nitrous oxide are released into the atmosphere, making land degradation one of the most important contributors to climate change (Raimondo *et al.*, 2021). Sub-Saharan Africa (SSA) needs to increase the production of food crops, and this need will multiply in the future. Although part of the demand will be met by the cultivation of new land, it must be met by raising the productivity level of land already cultivated (FAO, 2011).

Land degradation represents a critical challenge in Nigeria, affecting regions across the entire country. Nigeria frequently ranks among the most at-risk nations globally on degradation indices (Foundation, 2020). The extent of degraded land in the country surpasses 238,533 square kilometers (World Bank, 2016). Despite this, Nigeria's rapidly growing population, one of the fastest in the world, faces only marginal increases in food production rates (Aina *et al.*, 2019). Key drivers of degradation include soil erosion, loss of organic matter and plant nutrients, and soil compaction—factors that pose significant threats to food security (Aina *et al.*, 2019). Thus, although some regions boast expansive land and fertile soils, mismanagement remains a

formidable obstacle to achieving sustainable food security (Fajobi *et al.*, 2022). Land productivity, defined as the ability of soil to sustain crop yields and support biomass, is influenced by both human activities and natural factors, including precipitation, soil properties, topography, pest and disease incidence, and land management practices (Eswaran *et al.*, 2019). Monitoring changes in biomass trends or land productivity serves as a vital metric for evaluating land transformations and long-term land quality alterations (De La Fuente *et al.*, 2020). Vegetative cover dynamics provide a proxy measure for the overall productivity of a given land or human-environment system. Geographic Information Systems (GIS) and earth observation technologies offer effective tools for analyzing land productivity and tracking biomass changes across spatial and temporal scales (Bernard *et al.*, 2022).

A recent World Bank report reveals that 47% of Nigeria's population now lives below the international poverty line of \$2.15 per day. The declining trajectory of Nigeria's agricultural sector is most evident in the Sudan-Sahel region, where agriculture once served as the economic backbone but has lagged behind in key economic indicators over the past four decades (World Bank, 2023). Although substantial research has been conducted on land degradation assessment in Nigeria, there remains a lack of comprehensive analysis on the specific causes hindering the development of targeted solutions (Adenle

et al., 2020). This gap is particularly pronounced in the Sudan-Sahel Savannah region, a data-deficient area where agriculture underpins the livelihoods of 70% of households and over 50% of the population lives in poverty (Sedano *et al.*, 2020). Recent studies, such as that by Adele *et al.* (2020), which analyzed human-induced degradation between 2003 and 2018, primarily focused on the Guinea Savannah ecological zone, leaving the Sudan-Sahel region—forecasted to undergo significant changes in the future—largely unexplored.

Consequently, there is an urgent need to investigate the relationship between land productivity changes and their driving forces. Understanding this nexus is essential for promoting sustainable soil use and enhancing soil productivity to support livelihoods in the region. Addressing these challenges could provide critical insights for policymakers and empower farmers with knowledge to optimize soil management practices. Such efforts would not only boost agricultural productivity but also improve livelihoods, fostering resilience and sustainability in the Sudan-Sahel Savannah region.

The aims and objectives are:

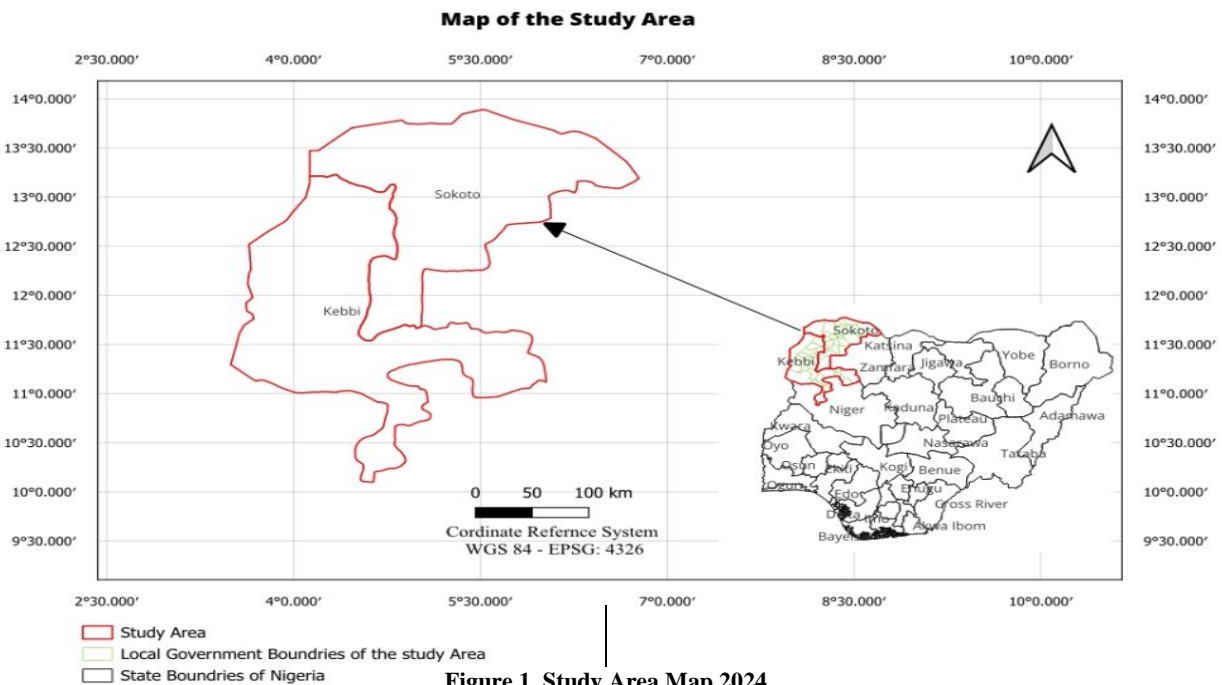
- i. To assess the degrading areas in Sokoto and Kebbi States, Nigeria.
- ii. To identify the various forces and their relative roles contributing to the land degradation in Sokoto and Kebbi, Nigeria.
- iii. To map the degrading areas in Sokoto and Kebbi States, Nigeria.
- iv. To offer possible solutions to curtail if not control the higher rate of degradation in the region.

We hypothesized that human activities have more influence on land degradation over the climatic factors in the region.

2.0. MATERIALS AND METHODS

2.1. Study Area

The area of study is Sokoto and Kebbi Zone in Sudan-Sahel Region of Nigeria. Sokoto and Kebbi lie between Latitude 12°30' North and Longitude 5°00' east. The study Area borders Niger to the north, and Benin and Niger to the west. The region covers an area of 42,432 square kilometers and is part of the Sudan Savannah agroecological zones (fig.1).



2.2. Data Sources and Pre-Processing

2.2.1. MODIS NDVI Time-Series

NDVI time-series data were acquired from MODIS NDVI products, offering a 500 m spatial resolution (Zhu *et al.*, 2021). MODIS was selected for its robust capacity to deliver consistent, long-term records of vegetation dynamics, enabling the detection of temporal changes in vegetation (Montfort *et al.*, 2021). The dataset, spanning 2001–20221, covered the Sudan-Sahel Region of Nigeria and was used to analyze NDVI trends as proxies for biomass productivity changes (Leroux *et al.*, 2017). The MODIS product underwent corrections for molecular scattering, ozone absorption, and aerosols (Didan *et al.*, 2015). To minimize residual noise that may affect the NDVI signal, pre-processing was performed using a Savitzky–Golay filter (third-order polynomial, 18-window size) to smooth data while preserving trend integrity (Wang *et al.*, 2019). Annual cumulative NDVI values (January 1–December 31) were calculated for each pixel (Montfort *et al.*, 2021).

2.2.2. Rainfall Data

Given the sparse and irregular distribution of rain gauges in the study area, rainfall data were sourced from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) dataset. CHIRPS has been validated over the Greater Horn of Africa, outperforming African Rainfall Climatology version 2 (ARC2) and Tropical Applications of Meteorology using Satellite data (TAMSAT3) in skill, bias, and error metrics (Dinku *et al.*, 2018). Data for the 2001–2021 period were resampled to align with MODIS NDVI spatial resolution (500 m) using the nearest-neighbor method (Montfort *et al.*, 2021).

2.2.3. Air Temperature

Data Air temperature data were obtained from the ERA5-Land dataset, which reliably captures temperature trends for scientific analyses (Zhao and He, 2022). Maximum annual average temperatures for the 2001–2021 period were computed and resampled to match the spatial resolution of MODIS NDVI data (500 m) using the nearest-neighbor method.

2.3. Land Productivity Change Analysis

2.3.1. NDVI Trend Analysis

Land degradation patterns were evaluated through statistical trend analyses applied to 22 years of annual MODIS NDVI data (2000–2022). The non-parametric Mann-Kendall (MK) test was employed, capable of detecting trends from as few as four samples. The MK test generates a tau coefficient ranging from -1 to 1, where positive values indicate productivity gains, and negative values indicate degradation. Trend significance was determined at a 95% confidence level (P -value < 0.05). Pixels were categorized into significant increases, significant decreases, and non-significant trends.

2.3.2. NDVI-Climate Correlation

Pearson correlation analysis was used to examine the relationships between annual cumulative NDVI, rainfall, and temperature values. Pearson's coefficient (r) quantifies the strength (-1 to +1) and significance (P -value < 0.05) of these linear relationships (Mehmood *et al.*, 2024). After confirming linearity between NDVI and climatic variables, correlations were computed for each pixel over the 2001–2021 period to identify significant relationships.

2.3.3. NDVI Residual Trend Analysis

Residual trend (RESTREND) analysis was conducted to assess productivity trends not explained by climate variables. This involved subtracting predicted NDVI (based on rainfall and temperature via linear regression) from observed NDVI values (Gedefaw *et al.*, 2021 and Irisarri *et al.*, 2021)). Only pixels with significant NDVI-climate correlations (P -value < 0.05) were included in the residual analysis, ensuring relevance (Tiwari *et al.*, 2024). This approach identifies vegetation productivity changes attributable to non-climatic factors (Montfort *et al.*, 2021; Leroux *et al.*, 2017).

2.3.4. Land Productivity Change Factor

This study assumed that productivity changes are driven primarily by climatic and human factors, consistent with Montfort *et al.* (2020) and Leroux *et al.* (2017). Analysis distinguished climate-induced changes (rainfall and temperature trends) from those caused by human activities, such as land management practices and associated environmental impacts, to attribute relative contributions to observed NDVI changes.

2.3.5. Data Analysis

Used Image analysis, enhancement, pre-processing, and statistical analyses were conducted using Google Earth Engine (GEE). Raster visualization and map preparation utilized QGIS, an open-source GIS software. Microsoft Office tools, including Excel, supported spreadsheet analysis, document preparation, graphing, and database management.

3.0. RESULTS

31.06% of the study area exhibited a significant decline in NDVI values, indicating widespread land degradation (Table 1). These degraded regions are predominantly concentrated in Kebbi State, specifically within the local government areas of Danko-Wasagu, Sakaba, and parts of Ingaski, located in Nigeria's Tropic Warm Semi-arid Region. Conversely, 23.41% of the total area demonstrated stable or improving NDVI values, signifying non-degraded land. These regions were predominantly observed in Sokoto State, particularly in Gwadabawa, Binji, Gada, Illela, Bodinga, Wamakko, and parts of the state. The remaining 45.53% of the combined areas in Kebbi and Sokoto States showed no significant biomass changes over the analysis period (Figure 2).

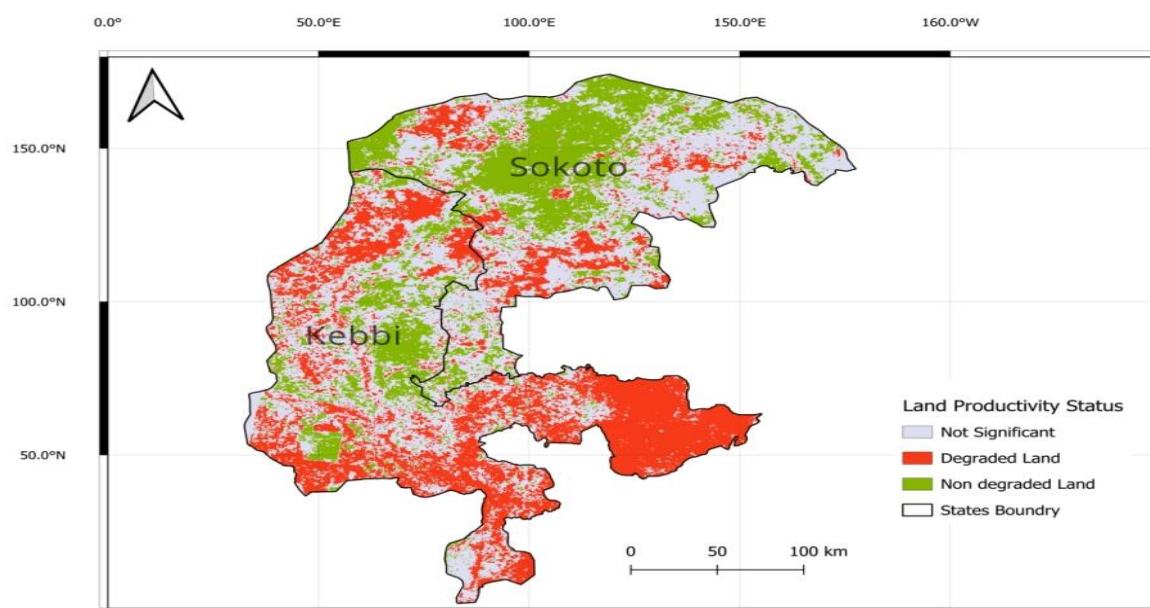


Figure 2: Spatial Distribution of Land Productivity Changes in Sokoto and Kebbi States (2001–2011)

3.1. NDVI-Climate Correlations

The NDVI-climate correlation analysis revealed noteworthy causal relationships, particularly the positive association between NDVI and rainfall and the negative association between NDVI and temperature. These relationships were integrated into the classification of driving factors (Table 2). The findings indicate that 92.96% of the study area showed no significant correlation between NDVI and rainfall, and 99.53% exhibited no significant correlation with temperature. However, 6.06% of the analyzed pixels displayed a significant positive correlation between NDVI and rainfall (Table 3). These pixels were predominantly located in Dange-Shuni, Isa, Goronyo, Tangaza, and Kware local government areas of Sokoto State, where precipitation significantly increased during the study period (Figure 4). Conversely, the spatial extent of significant NDVI-temperature correlations was minimal, with only 0.98% of the area showing negative correlations (Table 3). These pixels were scattered and did not align with regions of significant temperature increases (Figure 4). These results underscore that rainfall exerts a stronger influence on NDVI trends than temperature, emphasizing the critical role of precipitation in driving vegetation dynamics in the region.

Table 2: Spatial Analysis of NDVI-Climate Correlation and Residual Trend Dynamics in Sokoto and Kebbi States

	Not Significant		Positive (P-value<0.05)		Negative (P-value<0.05)	
	Km ²	%	Km ²	%	Km ²	%
NDVI-Rainfall Correlation*	6,283,143	92.96	409,825	6.06	66,137	0.98
NDVI-Temperature Correlation*	6,542,573	99.53	27,284	0.42	3312	0.05
NDVI-Rainfall Residual Trend**	5,290,267	77.25	207,760	3.03	1,350,099	19.71
NDVI-Temperature Residual Trend**	5,598,696	81.76	123,534	1.80	1,125,898	16.44

The RESTREND analysis, applied to pixels with significant positive NDVI-rainfall correlations and negative NDVI-temperature correlations, revealed that most NDVI trends were adequately explained by climatic factors alone. Specifically, 77.25% of the pixels analyzed in the NDVI-precipitation model and 81.76% of those in the NDVI-temperature model exhibited no significant residual trends after climate correction. This outcome suggests that climate factors predominantly account for the observed NDVI variations in these areas.

Among the residual trends indicating potential influences beyond climate, 16.44% of the negative NDVI-temperature correlated pixels showed a decreasing trend in residuals, while 3.03% of the positive NDVI-rainfall correlated pixels exhibited an increasing trend. These findings point to areas where human activities likely contribute to changes in land productivity alongside climatic drivers. However, when considering the entire study area of Sokoto and Kebbi States, the spatial extent of these residual trends was negligible, underscoring the dominant role of climatic factors in driving vegetation dynamics across the region.

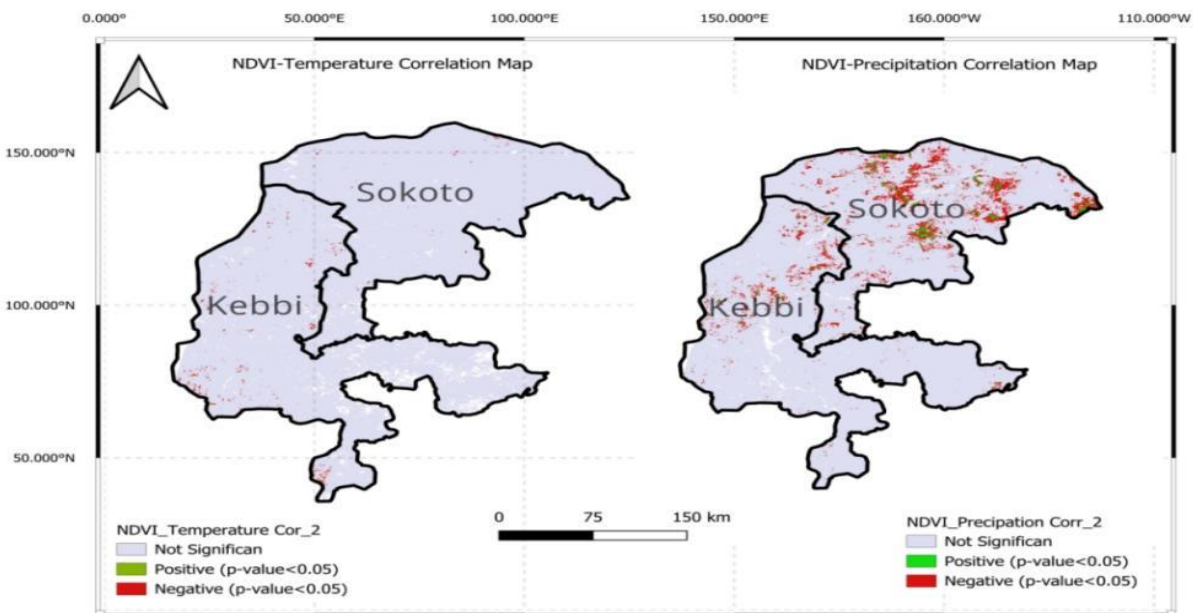


Figure 3: NDVI-Climate Correlation (2001-2021).

3.2. Land Productivity Driving Factors

Human activities were the predominant drivers of land productivity decline in the study area between 2001 and 2021, accounting for nearly the entirety (99%) of the observed decreasing trend. In contrast, climate change factors contributed to only 0.5% of the decline, while the combined influence of human and climatic factors was minimal, at just 0.09%.

When examining the total area, 45.53% of the land experienced degradation attributed to human-induced activities. These areas were primarily concentrated in Kebbi State, specifically in the local government areas of Danko-Wasagu, Sakaba, and parts of Ingaski (Table 3; Figure 4). These findings underscore the overwhelming impact of anthropogenic factors on land productivity dynamics, highlighting the need for targeted interventions to address unsustainable land use practices in the region.

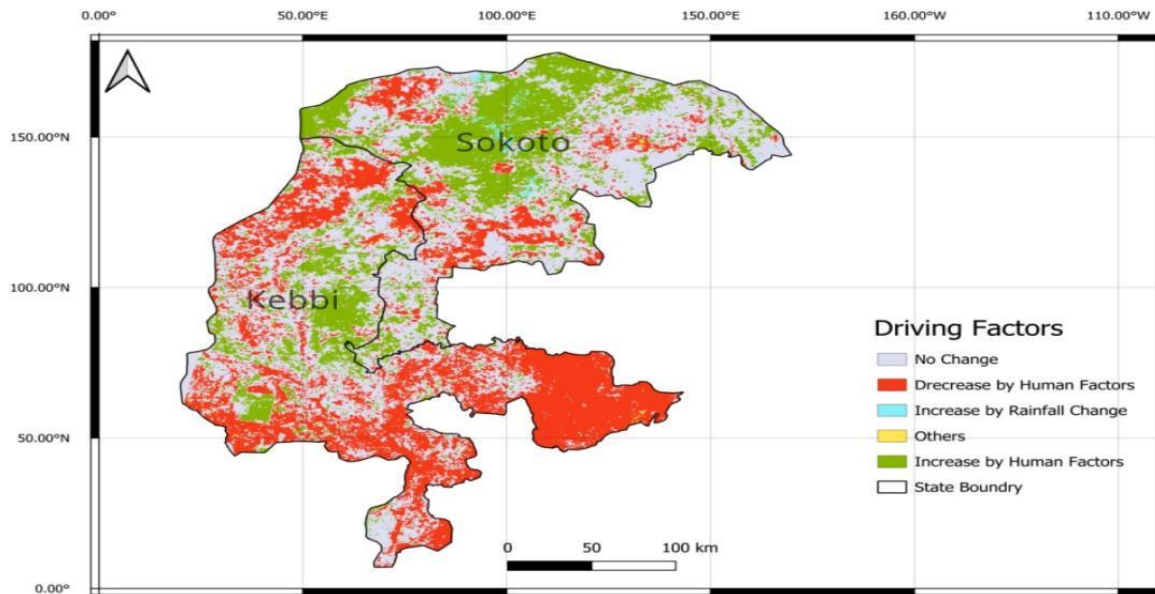


Figure 4: Land Productivity Trend Driving Factors Map

Human activities were the dominant drivers of the positive NDVI trend observed in the study area, accounting for 96.8% of the overall increase in land productivity. Among climatic factors, rainfall was the only variable with a spatially significant impact, contributing to 3.03% of the positive trend. The combined influence of climate change and human factors was minimal, accounting for just 0.17% of the observed improvements.

Table 3: Total (Ha) and Relative (%) Area of the Driving Factors Classes of Land Productivity Changes in the Sokoto and Kebbi States.					
NDVI trend (P value<0.05)		Change driving factors	Area over Kebbi and Sokoto		
			Ha	%	
Decrease (Tau<0)	Climate	RC	11,884	0.17	0.22
		TC	3672	0.05	

		TC+RC	49	0.0	
	Climate + Human	RC+HF	1993	0.03	0.04
		TC+HF	414	0.01	
		RC+TC+HF	0.0	0.0	
	Human	HF	2,120,312	45.53	45.53
Increase (Tau>0)	Climate	RC	48,802	0.71	0.71
		TC	49	0.0	
		RC+TC	0.0	0.0	
	Climate + Human	RC+HF	2,539	0.04	0.04
		TC+HF	24	0.0	
		RC+TC+HF	0.0	0.0	
		Human	HF	1,560,143	22.66
Not Significant			3,134,075	45.53	45.53

RC = Rainfall change, TC = Temperature change, HF = Human factor

In the study area, 22.66% of the land experienced an increase in productivity attributed to human activities, with the majority of these areas located in Sokoto State. Specifically, the local government areas of Gwadabawa, Binji, Gada, Illela, Bodinga, and Wamakko were identified as key zones of human-induced productivity gains. Meanwhile, rainfall contributed to a productivity increase in 0.71% of the total area, primarily concentrated in Sokoto State within the local government areas of Kware, Gwadabawa, Tangaza, and Gada (Table 3; Figure 4). These findings underscore the pivotal role of human interventions in driving land productivity improvements, complemented by localized climatic contributions.

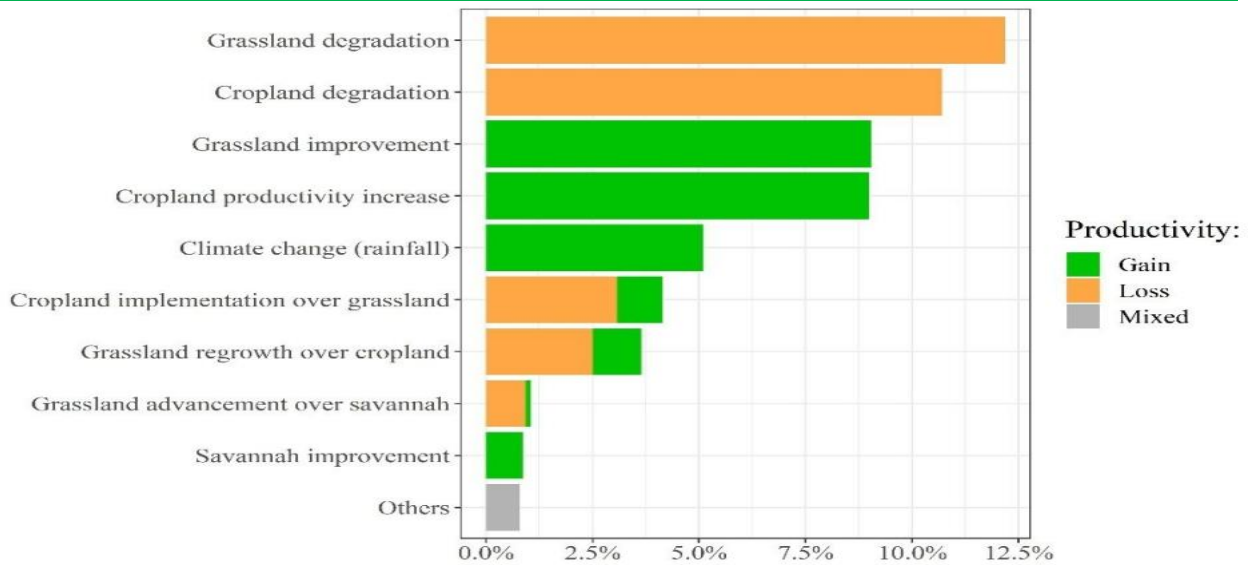


Figure 5. Relative areas of the categories of change factors in the study area and their roles in the gain and loss of productivity (Yabo at al .,2024)

The main category of productivity decline associated with human activity was grassland degradation, which represented 12% of the study area, followed by cropland degradation (10.5%) (Figure 6). Grassland degradation was more relevant in the eastern and western NNR states, such as Niger and Yobe, whereas cropland degradation was more important in the central and southern states, particularly in Adamawa, Plateau, and Kaduna (Figure 6).

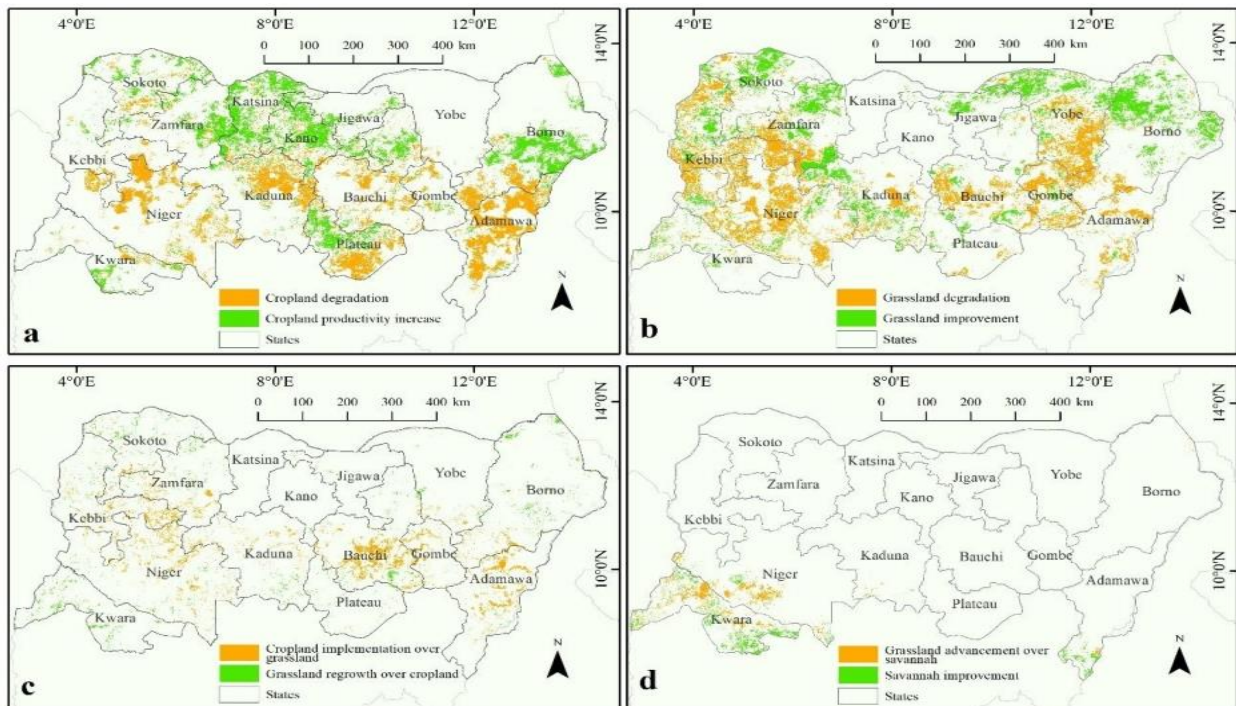


Figure 6. Spatial distribution of the main factors in land productivity changes induced by human activities: a) cropland; b) grassland; c) cropland-grassland conversion; d) Savannah. Colors: Orange represents a decrease, and green represents an increase in productivity. (Source: Ibrahim Yabo et al., 2024).

4.0 DISCUSSION

The study findings reveal distinct spatial variations in land degradation, productivity improvements, and stable regions (Figure 3). In Sokoto State, productivity increases were noted in Gwadabawa, Binji, Gada, Illela, Bodinga, and Wamakko Local Government Areas, which fall within the Sahelian and Sudan Savannah ecological zones. These areas, characterized by desert and semi-arid conditions, contrast with significant degradation observed in Kebbi State, particularly in Danko-Wasagu, Sakaba, and parts of Ingaski, located within the Sudan and Guinea Savannah ecosystems (Figure 1).

This pattern presents a paradox: productivity decline is more pronounced in ecologically wetter zones with higher primary productivity, whereas improvements occur in regions with sparse vegetation and harsh climatic conditions. This aligns with Mustapha (2020) and Adenle *et al.* (2020), who reported widespread degradation in the Guinea Savannah with localized improvements in Zamfara and Katsina. Similarly, an NDVI trend analysis (2000–2015) by Leroux *et al.* (2017) documented increasing productivity near the Niger border alongside localized declines further south.

Climatic and human factors contributed to productivity changes, with human influence playing a dominant role, consistent with previous studies in Northern Nigeria (Osunmadewa *et al.*, 2018). Since the 1990s, increasing rainfall has been recorded in the Western Sahel (Nicholson, 2005), with an annual increase of 8–10 mm in Northern Nigeria between 1981 and 2007 (Fensholt *et al.*, 2012). Studies have linked this trend to Sahel greening (Eklundh & Olsson, 2003; Hickler *et al.*, 2005), reflected in our findings (Figure 4). Additionally, Lu *et al.* (2020) observed precipitation-driven re-greening in the Savannah region.

However, vegetation response to rainfall varies. Capecchi *et al.* (2008) found Sahelian vegetation more sensitive to rainfall fluctuations than its moister southern counterparts. In contrast, our study indicates that rainfall had a minimal impact on biomass increase, underscoring human activities as the primary driver of land degradation (Figure 5). This contradicts earlier claims by Prince *et al.* (2004) and Tucker *et al.* (1991) that Sahara-Sahel boundary shifts are entirely rainfall-dependent. While some studies highlight a negative correlation between NDVI and temperature in Northern

Nigeria due to thermal stress (Nwilo *et al.*, 2020), our analysis found no direct temperature influence on land degradation patterns (Figure 4). Thus, climate change had a limited impact on NDVI trends in the study area from 2001 to 2021 (Figure 5).

Human activities, including land use changes, significantly influenced both degradation and biomass increase (Figure 4). Productivity improvements, particularly in Sokoto State, align with studies by Leroux *et al.* (2017) and Olsson *et al.* (2005), which emphasize the role of human interventions in Sahel greening. Restoration initiatives, such as the FAO's Action Against Desertification program and the Great Green Wall project, have contributed to vegetation recovery by promoting sustainable land management and combating desertification (FAO, 2023; Gadzama and Ayuba, 2016).

Despite biomass increases along the Nigeria-Niger border, Ibrahim *et al.* (2018) noted that afforestation efforts with drought-resistant exotic species have reduced native flora diversity and density. This suggests that while greening has occurred, ecological health may still be at risk, warranting further study.

While human activities foster productivity gains, they also drive land degradation, particularly in grasslands and croplands, which accounted for approximately 9% of total degradation (Table 3, Figures 4 and 5). The most severe degradation was observed in Danko-Wasagu, Sakaba, and parts of Ingaski in Kebbi State, where cropland expansion over grasslands and the regrowth of grasslands over abandoned farmlands were the dominant land-use changes. Cropland expansion was more strongly associated with declining productivity, whereas grassland regrowth contributed to improvements (Figure 5). Mansur (2024), identified logging and overgrazing as critical contributors to land degradation in Kebbi State, which hosts approximately 90% of Nigeria's cattle population.

Our findings suggest that agricultural intensification, rather than cropland expansion, had a more significant impact on land degradation (Figure 6). Most virgin land in the study area was cleared before 2001, aligning with Sedano *et al.* (2019), who reported that Northern Nigeria's arable land is largely cultivated, with current efforts focused on increasing farming intensity. Unsustainable agricultural practices—including

reduced fallow periods, continuous cropping, excessive tillage, improper agrochemical use, bush burning, and monocropping—have significantly contributed to land degradation (Babagana *et al.*, 2020; Ibrahim *et al.*, 2018).

5. CONCLUSION

This study analyzed land productivity dynamics in Sokoto and Kebbi States, Nigeria, to assess land degradation and improvement patterns between 2001 and 2021. The findings reveal spatial variations in land degradation, with drier regions near the Nigeria-Niger border experiencing increased productivity, while the more humid southern areas exhibited declining productivity.

The observed productivity increase in Sokoto and limited areas of Kebbi aligns with the broader trend of Sahel greening, driven primarily by human-induced factors such as land abandonment, migration, and land recovery initiatives. Conversely, land degradation continues to be driven predominantly by unsustainable practices, including overgrazing and excessive agricultural exploitation. Logging has also significantly contributed to land degradation in Kebbi State due to the absence of afforestation or restoration efforts, with an individual exploiting approximately 4 to 7 trees per year, posing severe environmental risks (Mansur M. A., 2024).

Given the socioeconomic and environmental vulnerabilities of Northern Nigeria, it is imperative to implement integrated land restoration strategies. Our findings underscore the importance of reforestation and conservation-focused land management while identifying critical hotspots for urgent rehabilitation. Furthermore, supporting herders and farmers with sustainable alternatives is essential for reducing pressure on land resources. These findings contribute to the broader understanding of land degradation trends and can inform policies aimed at achieving land degradation neutrality in Nigeria by 2030, in alignment with the UNCCD (2015).

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