

Spatio-Temporal Dynamics of Vegetation Health in the Southern Guinea Savannah Agro-Ecological Zone of Taraba State, Nigeria

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ABSTRACT

Vegetation health is a critical indicator of ecosystem resilience, agricultural productivity, and climate regulation, yet it is increasingly threatened by anthropogenic pressures and climatic variability. This study assessed the spatio-temporal dynamics of vegetation health in the Southern Guinea Savannah (SGS) agro-ecological zone of Taraba State, Nigeria, over 37 (1987–2024). Multi-temporal Landsat and Sentinel-2 imagery were processed to surface reflectance, cloud-masked, and analyzed using the Normalized Difference Vegetation Index (NDVI). Change detection and Mann–Kendall trend analyses were employed to quantify temporal trajectories, while Getis-Ord Gi* hotspot analysis identified degradation centers and conservation refugia. Results revealed a progressive decline in vegetation health, with dense forest cover (NDVI ≥ 0.61) contracting from 21.5% of the landscape in 1987 to isolated patches confined to the southeast by 2024. Degradation hotspots expanded eastward and consolidated into large contiguous zones in the northwest and central regions, while refugia fragmented into riparian corridors. The findings highlight severe erosion of ecosystem services, including biodiversity conservation, carbon sequestration, and watershed protection. Urgent interventions are required to safeguard remaining refugia and restore degraded landscapes in alignment with the Sustainable Development Goals and the Great Green Wall Initiative.

Keywords: Aboveground Biomass (AGB), Guinea Savannah, Normalized Difference Vegetation Index (NDVI), Spatio-Temporal & Vegetation Health

Introduction

Vegetation plays a central role in regulating ecological processes, supporting livelihoods, and maintaining environmental stability. Healthy vegetation cover regulates the hydrological cycle, prevents soil erosion, stores carbon, and sustains agricultural productivity [1]. In savannah ecosystems, vegetation also underpins livestock production, biodiversity conservation, and fuelwood supply, making it an indispensable resource for rural communities [2]. Monitoring vegetation health, therefore, has become a critical component of environmental management and climate adaptation strategies. The Southern Guinea Savannah (SGS) zone of Nigeria represents a transitional ecosystem between the forest belt in the south and the Sudan Savannah in the north. It is characterized by a mosaic of grasses, shrubs, and scattered trees, making it highly productive for farming and grazing [3] (Ayoade, 2004). This ecological zone, including parts of Taraba State, is recognized as Nigeria's "food basket," yet it remains highly vulnerable to climatic variability, unsustainable land use practices, and population growth. The expansion of agriculture, fuelwood extraction, grazing pressure, and settlement encroachment has accelerated vegetation loss in the region [4].

At the global scale, spatio-temporal analyses of vegetation dynamics have revealed strong linkages between vegetation greenness and climatic drivers, particularly rainfall and temperature [5, 6]. In Africa, satellite-based studies show mixed patterns of "greening" and "browning" depending on rainfall variability, land use intensity, and ecological context [7].

In West Africa, the Sahelian region is widely studied due to desertification concerns, but less attention has been directed to the Guinea Savannah belt despite its agricultural importance and increasing vulnerability to climate-induced stresses.

In Nigeria, several studies have documented vegetation decline in different ecological zones. Idisi, Lawal, and Deekor [8] reported a long-term reduction in NDVI across South-South Nigeria, attributing the decline to climate variability and human activities. Similarly, Osunmadewa, Wessollek, and Karrasch [9] observed inconsistent greening patterns in the Guinea Savannah using Advanced Very High-Resolution Radiometer (AVHRR) data, with rainfall emerging as the primary driver of variability. In Taraba State specifically, Joshua, Ojeh, and Atuma [10] found a significant reduction in vegetation cover in Kurmi Local Government Area, with about 24% of vegetation lost between 2010 and 2020. These findings reinforce evidence that the Guinea Savannah zone is undergoing rapid landscape transformation, threatening its ecological balance and agricultural potential.

Despite these valuable contributions, major research gaps persist. First, most previous studies in Nigeria emphasize vegetation *cover change* without explicitly assessing vegetation *health*, which reflects the vigor, greenness, and stress levels of vegetation over time. Second, spatio-temporal analyses that integrate climatic and anthropogenic drivers of vegetation dynamics remain limited in the SGS zone of Taraba State. Third, little attention has been given to identifying degradation *hotspots* and resilience zones that can guide sustainable land management.

Addressing these gaps is essential for aligning regional land-use practices with Nigeria's commitments under global environmental frameworks, including the United Nations Sustainable Development Goals (SDGs 13 and 15) and the Great Green Wall Initiative.

This study, therefore, investigates the spatio-temporal dynamics of vegetation health in the Southern Guinea Savannah agro-ecological zone of Taraba State, Nigeria. Using geospatial datasets and remote sensing techniques, it aims to: (1) assess temporal trends in vegetation health over three decades; (2) map spatial patterns and identify areas of vegetation decline or improvement; and (3) examine the influence of climatic and anthropogenic factors on vegetation health dynamics. The findings are expected to provide critical insights for policymakers, land managers, and local communities in developing strategies for sustainable ecosystem management and climate resilience in the region.

Materials and Methods

This study employed a remote sensing and GIS-based approach to assess the spatio-temporal dynamics of vegetation health in the Southern Guinea Savannah agro-ecological zone of Taraba State, Nigeria. The methodology was structured around the acquisition of multi-temporal satellite imagery, preprocessing of datasets, computation of vegetation indices, estimation of aboveground biomass, change detection, and hotspot analysis of degradation. Each step was carefully designed to ensure methodological robustness, reproducibility, and alignment with best practices in vegetation monitoring.

Study Area and Data Acquisition

The Southern Guinea Savannah (SGS) agro-ecological zone of Taraba State was delineated using administrative boundary data and ecological zone layers, projected into the Universal Transverse Mercator (UTM) coordinate system appropriate for Nigeria. This ensured consistency in area calculations and spatial overlays. Ancillary geospatial datasets, including the Shuttle Radar Topography Mission (SRTM) 30 m digital elevation model, were integrated to capture terrain characteristics such as slope and aspect that influence vegetation patterns. Additional contextual data, such as roads, rivers, and settlement layers, were incorporated to aid interpretation of degradation hotspots and accessibility-driven vegetation change [11].

Satellite imagery formed the core dataset. Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) were used for 1987 and 2004, respectively, while Landsat 8 Operational Land Imager (OLI) was selected for 2014. For 2024, imagery was sourced from Landsat 8/9 OLI and Sentinel-2 MultiSpectral Instrument (MSI), which provide higher spatial resolution (10–20 m) but were resampled to 30 m to maintain comparability with the Landsat archive. Only surface reflectance products were used to minimize atmospheric distortion. Imagery was obtained from the USGS Earth Explorer portal and the Google Earth Engine (GEE) platform, which offers access to preprocessed collections and allows efficient cloud-based computation [11, 12]. Selection criteria included a phenological window corresponding to the dry season (November to March) to minimize seasonal variability, and a cloud cover threshold of less than 10% over the study area.

Preprocessing of Satellite Data

All images underwent radiometric and atmospheric correction. For Landsat Collection 2, the Land Surface Reflectance Code (LaSRC) algorithm was applied, while Sentinel-2 images were atmospherically corrected using Sen2Cor. Cloud and shadow contamination were addressed through the Function of Mask (Fmask) algorithm, which detects and removes clouds and their shadows, ensuring that NDVI calculations were based only on reliable pixels [13].

Geometric alignment was standardized across all datasets by co-registering imagery to the same UTM projection. To harmonize sensors with different resolutions, Sentinel-2 bands were resampled to 30 m using bilinear interpolation, thereby avoiding pixel mismatch when integrating with Landsat datasets. Harmonized Landsat–Sentinel (HLS) products were also consulted to ensure consistency in reflectance scaling and band calibration [14]. Preprocessing was validated through visual inspection of histograms, cloud masks, and scene overlays to ensure consistency across epochs.

Computation of NDVI and Classification

The Normalized Difference Vegetation Index (NDVI) was calculated for each composite year (1987, 2004, 2014, and 2024) using the standard formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Where the Near-Infrared (NIR) and Red bands correspond to sensor-specific band assignments (Landsat TM/ETM+: NIR = band 4, Red = band 3; Landsat 8 OLI: NIR = band 5, Red = band 4; Sentinel-2 MSI: NIR = band 8, Red = band 4) [15, 16].

For each target year, seasonal image composites were generated by calculating the median NDVI of all cloud-free scenes within the dry-season window. This approach reduces noise from atmospheric anomalies and ensures robust representation of vegetation condition for each epoch [12].

The NDVI rasters were subsequently classified into four vegetation health categories: very low ($NDVI \leq 0.20$), low ($0.21-0.40$), moderate ($0.41-0.60$), and high (≥ 0.61). Class boundaries were established through histogram analysis and natural breaks (Jenks) to reflect ecological transitions while maintaining comparability across the four years [17]. These thresholds were locked across all time steps to allow consistent spatio-temporal comparison.

Change Detection and Trend Analysis

Vegetation change was assessed using two complementary approaches. First, a post-classification comparison was undertaken by overlaying NDVI class maps across successive time periods (1987–2004, 2004–2014, 2014–2024, and 1987–2024). This generated “from-to” change matrices, quantifying conversions such as dense vegetation to degraded land or grassland to cropland. This method is intuitive and produces area estimates of land cover transitions, though it is sensitive to classification errors [18].

Second, a pixel-wise time-series analysis was conducted to capture long-term trends in vegetation health. The non-parametric Mann–Kendall test was applied to detect monotonic trends in NDVI, while Sen's slope estimator quantified the rate of change at each pixel. These methods are widely used for vegetation trend analysis as they are robust to non-normal distributions and missing data [19]. Significance was tested at the 95% confidence level, with correction for serial correlation where necessary.

The combination of post-classification and trend analysis provides both categorical and continuous perspectives on vegetation dynamics.

Hotspot Analysis

To identify degradation hotspots and conservation refugia, spatial statistical analysis was conducted using the Getis-Ord G_i^* statistic. This method detects clusters of high or low NDVI change values relative to a random distribution, thereby highlighting statistically significant zones of degradation (hotspots) and resilience (cold spots). The analysis was performed within a spatial weights matrix based on distance thresholds to account for local neighborhood effects [20]. To address the issue of multiple testing, a False Discovery Rate (FDR) correction was applied to reduce Type I errors [21]. Hotspot outputs were mapped across the four epochs, allowing the identification of primary, expanding, and consolidated degradation centers, as well as the contraction of conservation refugia.

Accuracy Assessment and Uncertainty Estimation

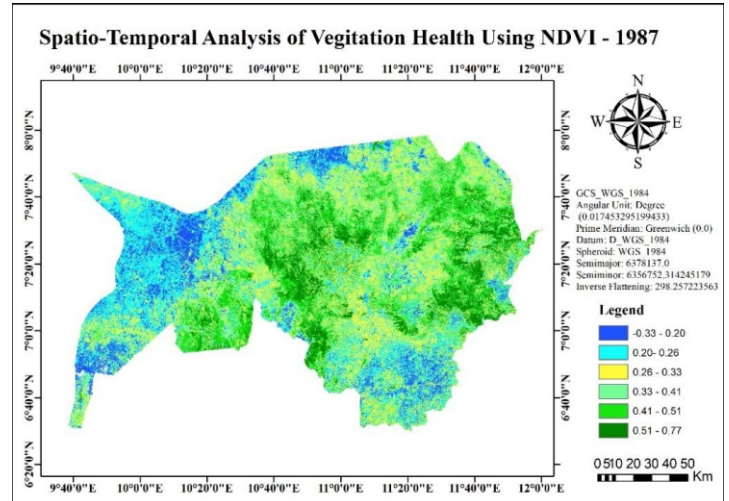
Accuracy assessment was carried out following the good practice guidelines of Olofsson [18]. A stratified random sampling design was employed to validate classified NDVI maps using high-resolution satellite imagery and field reference data. Confusion matrices were generated to calculate overall accuracy, users' and producers' accuracies, and the Kappa coefficient. In addition, area estimates were reported with confidence intervals to quantify uncertainty in land cover transitions. Trend analysis results were reported with p-values and Sen's slope values to ensure transparency in significance testing.

Result of the Findings

Spatio-Temporal Analysis of Vegetation Health using Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) was employed to quantitatively assess vegetation health, density, and photosynthetic activity across the Southern Guinea Savannah agro-ecological zone of Taraba State for the years 1987, 2004, 2014, and 2024. This analysis provides a critical, multi-temporal perspective on the trajectory of vegetation change, offering an indirect measure of the impacts of deforestation and forest degradation on the structural integrity of the ecosystem.

The 1987 vegetation health map (Fig. 1), derived from NDVI values, serves as the critical baseline against which all subsequent change is measured. It portrays a landscape that, while already showing signs of human influence, retained a robust and ecologically structured character. The most striking feature is a clear west-to-east gradient of improving vegetation health. The western and southwestern sectors are dominated by low NDVI values (illustrated in red and orange), classifying them as areas of bare soil and sparse vegetation. Covering 18.5% of the study area (1,850 km²), these zones were already subject to extensive clearance for agriculture, grazing, and settlements, indicating significant anthropogenic pressure predating the study period.



Map 1: Vegetation Health Map of the Study Area (1987)

The most extensive class on the map is the moderate-low NDVI zone (yellow), covering 32% of the area (3,200 km²), representing a transitional landscape of grasslands and degraded woodlands indicative of widespread but moderate disturbance, likely from shifting cultivation. In promising contrast, the central and southeastern regions are characterized by moderate-high to high NDVI values (light and dark green). These areas, accounting for 28% and 21.5% of the zone respectively, signify healthy shrublands, secondary forests, and core patches of dense forest. These ecologically stable zones were vital for biodiversity conservation, carbon sequestration, and providing a full suite of regulating ecosystem services. This 1987 baseline thus illustrates a landscape with a clear spatial organization, where significant intact forest cores persisted alongside areas of degradation, maintaining considerable ecological resilience and functional integrity.

By 2004, the NDVI map (Fig. 2) reveals a significant and alarming departure from the 1987 baseline, marking the definitive onset of an accelerated degradation phase. The most prominent change is the marked expansion of low-NDVI areas (red/orange), which aggressively spread, particularly throughout the northern and western regions. This expansion is a direct visual indicator of widespread land-clearing activities, unequivocally linked to agricultural expansion and settlement development.

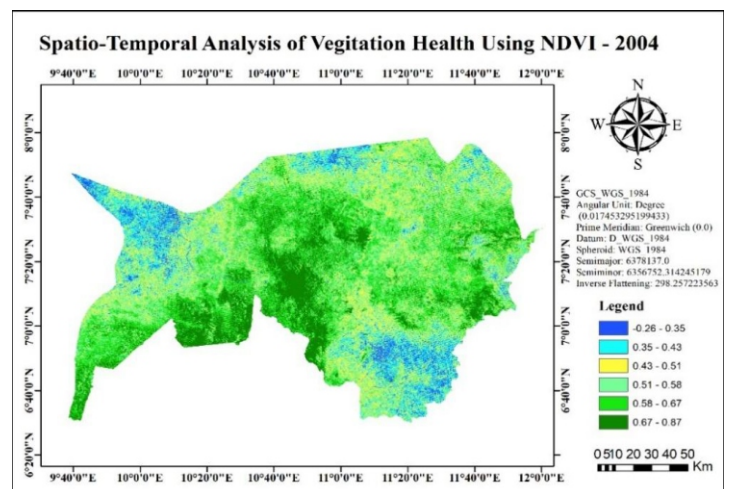


Fig. 2 Vegetation Health Map of the Study Area (2004)

A stark and emerging spatial dichotomy becomes apparent: a clear division between the heavily degraded north and west and the relatively healthier but increasingly threatened south and east. While patches of moderately healthy to dense vegetation (green) persisted in these southern and eastern zones, corresponding to the last remnants of intact forest patches and riparian corridors, a critical observation was the reduction in their spatial continuity and overall extent. These core areas were no longer expansive; they were becoming isolated islands under growing pressure. The map from this period effectively captures the landscape at a tipping point, where the rate of vegetation loss increased dramatically, and the spatial pattern of degradation began to consolidate into a clear and threatening frontier.

The 2014 NDVI map (Fig. 3) depicts a continuation and intensification of the destructive trajectory established by 2004, revealing a landscape in the throes of a full-scale ecological crisis. The aggressive expansion of degraded, low-NDVI areas did not abate; instead, it advanced deeper into the state's northern and, most critically, its central zones. This encroachment into the central areas signifies a transition to an advanced stage of deforestation and forest fragmentation, where previously connected vegetated areas were being dissected and consumed. The most alarming aspect of this map is the critical contraction of the core forest patches.

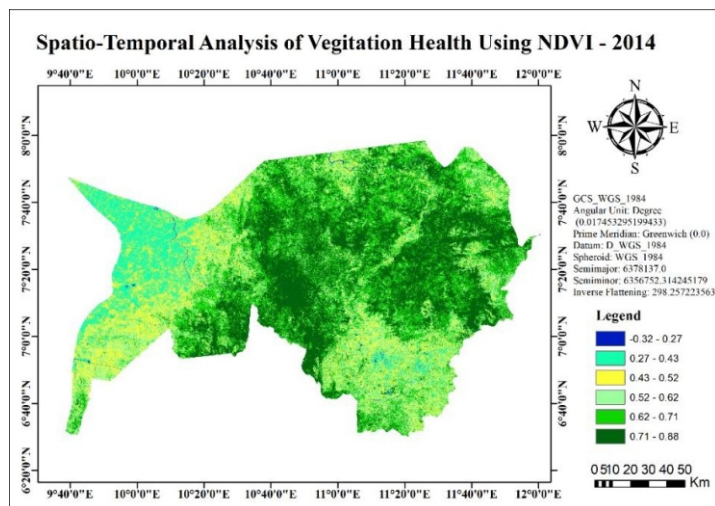


Fig. 3 Vegetation Health Map of the Study Area (2014)

The areas with the highest NDVI values (dark green), which represent the most ecologically functional parts of the landscape, were "noticeably reduced" compared to their 2004 extent. These vital refugia, now confined primarily to the south and along riparian corridors, were themselves becoming increasingly vulnerable to encroachment. Their fragmentation increases their susceptibility to edge effects, such as invasive species and microclimatic changes, and severely diminishes their ability to function as connected reservoirs for biodiversity. The 2014 map thus shows a landscape where degradation was not just expanding at the edges but was actively consuming and breaking apart the last remaining strongholds of ecological health.

The 2024 NDVI map (Fig. 4) presents a picture of near-complete transformation from the 1987 baseline, depicting a landscape overwhelmingly dominated by degraded and human-modified systems. The most dominant feature is the vast, contiguous expanse of land in the northwest and central regions characterized by very low NDVI values, indicating intensified land degradation and the near-complete removal of original

forest cover. The landscape is now predominantly a mosaic of moderate NDVI values (yellow and light green), reflecting a mix of degraded savannah, active croplands, and fallow areas.

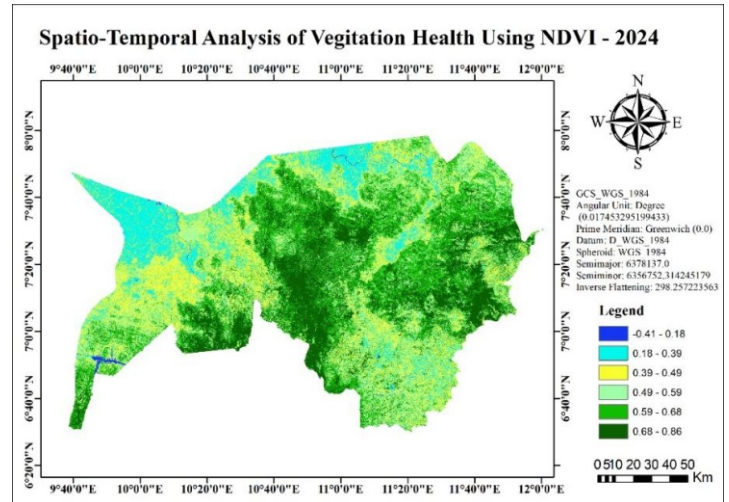


Fig. 4 Vegetation Health Map of the Study Area (2024)

This shift signifies that natural ecosystems have been largely replaced by anthropogenic systems with low ecological functionality and resilience. The highest NDVI values (dark green), representing healthy, dense vegetation, are now restricted almost exclusively to the southeastern and southern zones. These areas are the last remaining vestiges of the region's original ecosystem service capacity, but they persist under significant pressure and are highly isolated. Their restricted and fragmented nature poses a severe threat to their long-term survival and the survival of the species they support. Fig. 4 illustrates the outcome of the 37-year trend: a severe erosion of ecological resilience and a fundamental shift in the character of the biome from a functional savannah-forest mosaic to a fragmented, productivity-limited landscape.

Comparative NDVI Analysis (1987-2024)

The comparative NDVI analysis from 1987 to 2024 demonstrates a progressive and accelerating decline in vegetation health across the Southern Guinea Savannah of Taraba State. The temporal sequence of maps reveals a distinct trajectory of loss, where healthy vegetation cores that were concentrated in the northeast and central zones in 1987 gradually contracted southeastwards, while areas of degradation expanded outward from the west and northwest to engulf much of the central landscape. This transformation reflects the steady encroachment of agricultural expansion, deforestation, and other anthropogenic pressures. The shift from a landscape that contained a substantial proportion of dense vegetation (21.5% in 1987) to one increasingly dominated by moderate and degraded vegetation underscores the erosion of ecological resilience. Over time, the biome has undergone a fundamental shift in character, with shrinking forest cover, fragmented habitats, and declining ecosystem services such as carbon storage, soil protection, watershed regulation, and biodiversity conservation, leaving the region more vulnerable to environmental stresses and climate variability.

The spatio-temporal analysis of vegetation health in Taraba State, as presented in Table 1, revealed substantial shifts in land cover distribution between 1987 and 2024. Water bodies expanded remarkably from 94.66 km² (0.38%) in 1987 to 2,488.97 km² (9.91%) in 2024, reflecting nearly a 26-fold

increase. Similarly, bare or degraded land showed a significant upward trend, increasing from 3,295.97 km² (13.12%) in 1987 to 5,929.07 km² (23.60%) by 2024, indicating heightened land degradation. In contrast, dense and healthy vegetation initially declined from 5,104.42 km² (20.32%) in 1987 to 3,637.62 km² (14.48%) in 2004, experienced a peak at 7,830.85 km² (31.17%) in 2014, but declined sharply to 2,261.42 km² (9.00%) by 2024. Moderate vegetation followed a similar downward trajectory, dropping from 6,059.21 km² (24.12%) in 1987 to 3,875.94 km² (15.43%) in 2024. The classes of very low vegetation and low vegetation cover exhibited fluctuating patterns, with reductions observed in 2014 but moderate increases again in 2024. Collectively, these results highlight a long-term decline in dense vegetation and an expansion of degraded land and water surfaces, suggesting increasing pressure on the ecosystem and shifting land use dynamics.

Table 1: NDVI Class Coverage in Taraba State (2004–2024)

NDVI Class	Vegetation Condition	1987 Area (km ²)	1987 (%)	2004 Area (km ²)	2004 (%)	2014 Area (km ²)	2014 (%)	2024 Area (km ²)	2024 (%)
-0.42 to 0.20.	Water	94.66	0.38	1112.69	4.42	78.28	0.31	2488.97	9.91
-0.42 to 0.20	Bare/Degraded land	3295.97	13.12	3574.93	14.23	2619.45	10.43	5929.07	23.60
0.20 to 0.43	Very Low vegetation	4928.72	19.62	5114.56	20.36	3410.72	13.58	5823.14	23.18
0.20 to 0.43	Low vegetation cover	5636.69	22.44	6074.69	24.18	4646.87	18.50	4741.14	18.87
0.43 to 0.67	Moderate vegetation	6059.21	24.12	5605.18	22.31	6533.50	26.01	3875.94	15.43
0.67 to 0.87	Dense/Healthy vegetation	5104.42	20.32	3637.62	14.48	7830.85	31.17	2261.42	9.00
Total		25119.673	100%	25119.673	100%	25119.673	100%	25119.673	100%

The results of the one-way ANOVA test (Table 2) confirmed that these observed changes are statistically significant. The analysis produced a between-groups F-value of 12.86, which is considerably higher than the F critical value of 2.25, and a corresponding p-value of 1.62×10^{-8} , indicating a highly significant difference in vegetation health classes across the study years. This statistical evidence underscores that the spatio-temporal variations in vegetation distribution are not due to random chance but reflect systematic environmental changes in the Southern Guinea Savannah zone of Taraba State.

Table 2. ANOVA Analysis

Anova: Single Factor
SUMMARY

Groups	Count	Sum	Average	Variance		
1987 Area (km ²)	6	25119.67	4186.612	4907952		
1987 (%)	6	100	16.66667	77.75739		
2004 Area (km ²)	6	25119.67	4186.612	3312561		
2004 (%)	6	99.98	16.66333	52.52755		
2014 Area (km ²)	6	25119.67	4186.612	7787318		
2014 (%)	6	100	16.66667	123.3939		
2024 Area (km ²)	6	25119.68	4186.613	2541351		
2024 (%)	6	99.99	16.665	40.26179		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.09E+08	7	29808780	12.8559	1.62E-08	2.249024
Within Groups	92747377	40	2318684			
Total	3.01E+08	47				

Hotspot Analysis of Vegetation Health Degradation

A hotspot analysis was conducted implicitly through the spatio-temporal comparison of NDVI and Above-Ground Biomass (AGB) maps from 1987 to 2024. This analysis identifies areas that have undergone the most severe and concentrated vegetation loss, termed "degradation hotspots," as well as areas that have retained relatively healthy vegetation, termed "conservation refugia." The identification of these zones is critical for prioritizing intervention strategies and understanding the spatial dynamics of environmental change.

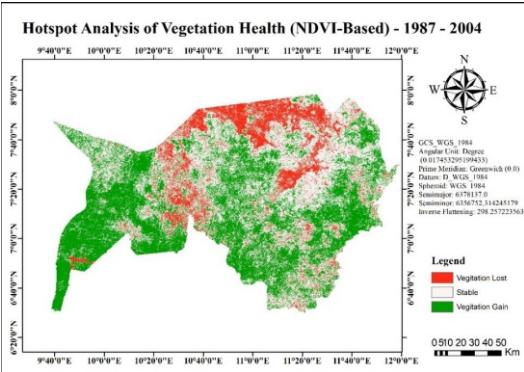


Fig. 5 Hotspot of Vegetation Health (1987-2004)

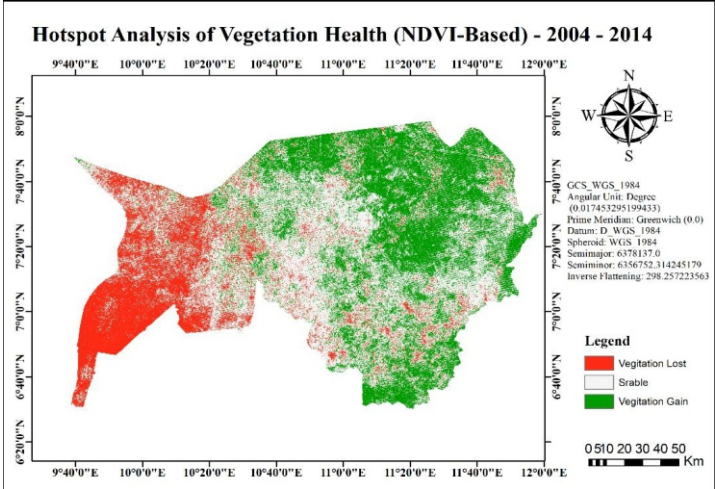


Fig. 6 Hotspot of Vegetation Health (2004-2014)

This hotspot analysis map for 1987 (Fig. 5) clearly identifies the primary epicenters of anthropogenic pressure at the beginning of the study period. It explicitly pinpoints the western and southwestern portions of the study zone as the "degradation hotspots." These areas, characterized by the lowest NDVI values

and biomass stocks, were already extensively cleared for agriculture, grazing, and settlements before 1987. They represented landscapes with minimal ecosystem service provision and served as the established launching points from which subsequent degradation would radiate. Conversely, Fig. 5 also identifies the primary "conservation refugia" in the northeastern, eastern, and central forest patches, which were characterized by high NDVI and high biomass. These zones functioned as critical carbon sinks and biodiversity reservoirs, forming the resilient core of the landscape's ecological functionality at the start of the monitoring period. This composite hotspot map for the period 2004-2014 visualizes the dynamic and aggressive expansion of degradation. It shows the original western and southwestern hotspots radiating outward, with the area of bare and degraded land increasing significantly by 56.8% (+1,050 km²). The analysis reveals that degradation did not spread uniformly but followed predictable pathways, such as accessibility routes along roads and rivers, pushing eastward to create new, secondary hotspots in the northern and central zones.

During this same period, the map illustrates the corresponding pressure on the conservation refugia, which suffered a severe 46.5% reduction in area (-1,000 km²). The refugia began to contract and fragment, indicating that the wave of degradation was not only expanding into new territory but also directly assaulting and reducing the core healthy areas of the landscape. The final hotspot map (2014-2024) (Fig. 7) reveals the catastrophic culmination of the documented trends. It shows a dramatic consolidation of degraded areas, where the original western hotspot merged with the newer northern and central hotspots to create a vast, contiguous area of severely depleted

ecological function that covered the majority of the study area. This unification of hotspots has created what can be termed "ecological deserts," large zones with minimal natural function that hinder seed dispersal and disrupt wildlife movement.

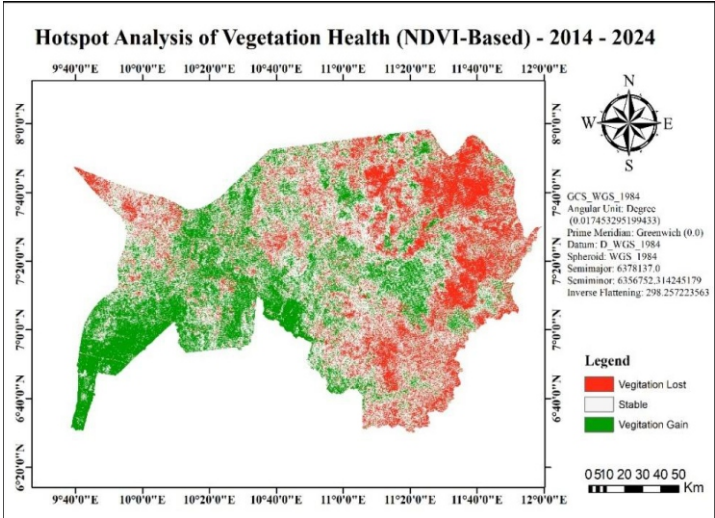


Fig. 7 Hotspot of Vegetation Health (2014-2024)

Simultaneously, Fig. 7 highlights the severe contraction and fragmentation of the conservation refugia, which by 2024 had been pushed almost exclusively into the southeastern and southern zones. These last remaining bastions of ecological health are now highly isolated and confined to less accessible terrain like steep riparian corridors, making their protection a matter of paramount urgency. This map provides the ultimate spatial prioritization for policymakers, unequivocally identifying the degradation fronts that must be halted and the final refugia that must be fortified to prevent a complete ecological collapse.

Table 3. Hotspot Loss and Gains

Class Name	1987 - 2004 - Area (km ²)	1987 - 2004 Area (%)	2004 - 2014 Area (km ²)	2004 - 2014 Area (%)	2014 - 2024 Area (km ²)	2014 - 2024 Area (%)
High Lost	1563.57122	6.22448875	2254.34912	8.97443657	2254.34912	8.97443657
Low Lost	3919.30862	15.60254634	4933.01462	19.63805269	4933.01462	19.63805269
Stable	6858.26042	27.30234753	7658.75462	30.48906974	7658.75462	30.48906974
Low Gain	8800.38482	35.03383511	7028.92562	27.98175605	7028.92562	27.98175605
High Gain	3978.14792	15.83678227	3244.62902	12.91668494	3244.62902	12.91668494
Total	25119.673	100	25119.673	100	25119.673	100

The analysis of hotspot losses and gains (Table 3) revealed dynamic transitions in vegetation cover across the study periods. Between 1987 and 2004, areas of vegetation gain were dominant, with low gain accounting for 35.03% and high gain 15.84%, while losses represented 21.82% of the landscape and stable areas 27.30%. In the subsequent period (2004–2014), vegetation loss intensified as high and low loss together rose to 28.61%, while gains declined to 40.90% and stable areas expanded slightly to 30.49%. The 2014–2024 estimates show a continuation of this pattern, suggesting stabilization of vegetation dynamics with consistent proportions of loss, gain, and stability. Overall, the results indicate that while vegetation gains were more prominent in the earlier period, losses became more pronounced after 2004, reflecting increasing pressures on the ecosystem despite areas of resilience.

Comparative Summary of Vegetation Degradation Hotspot Evolution (1987–2024)

Table 4. Comparative Summary of Vegetation Degradation Hotspot Evolution (1987–2024)

Period	Hotspot Characteristics	Spatial Dynamics
1987 (Baseline)	Primary hotspots in the western and southwestern zones; lowest NDVI (–0.1 to 0.2) and minimal biomass (0–10.31 t/ha); already cleared for agriculture, grazing, and settlements.	Established epicenters of degradation; localized but severe vegetation loss.
1987–2004	Expansion of degradation; 56.8% (+1,050 km ²) increase in bare and degraded land; degradation followed accessibility corridors such as roads and rivers.	Hotspots radiated outward from the west and southwest, forming secondary hotspots in the north and central zones.
2004–2014	Intensification of degradation corridors; continued expansion eastward; severe vegetation loss in northern and central areas.	Secondary hotspots solidified into persistent corridors of degradation.
2024	Catastrophic consolidation; northwestern and central regions merged into a vast contiguous hotspot; NDVI (–0.42 to 0.43); near-total removal of forest cover.	Unified degradation belt dominated the landscape; ecological collapse and loss of ecosystem services.

Table 4 highlights how vegetation health degradation hotspots evolved in the Southern Guinea Savannah of Taraba State over the 37-year study period, based on NDVI and AGB analysis. It shows the location, characteristics, and ecological implications for each time step.

In 1987 (Primary Hotspots – Baseline Stage), the hotspots were concentrated in the western and southwestern parts of the study area. These zones had very low NDVI values (-0.1 to 0.2) and low biomass (0 – 10.31 t/ha), indicating severe land degradation already in place before 1987. The areas were dominated by agriculture, grazing, and settlements, which meant that ecosystem services such as soil fertility, water regulation, and carbon sequestration were already severely diminished.

By 2004 (Expansion Phase), degradation had expanded outward from the original hotspots, covering more land in the west and northwest. There was a 56.8% increase in degraded land area ($+1,050$ km²), showing that human activity was rapidly spreading across the landscape. Accessibility factors such as roads and rivers played a critical role in directing this expansion, making these areas particularly vulnerable to further degradation.

In 2014 (Intensification and Secondary Hotspots), the process of vegetation decline intensified, with hotspots pushing eastward into the northern and central zones. These new zones became secondary centers of vegetation loss, connected to the older hotspots in the west and southwest. The result was a highly fragmented landscape, where forest patches shrank and became increasingly isolated, thus reducing ecological resilience.

By 2024 (Consolidation and Dominance), the hotspot analysis revealed a catastrophic consolidation. The northwestern and central regions had merged into a dominant, contiguous degradation belt. NDVI values dropped further (to around -0.42 to 0.43), showing an almost complete loss of vegetation health. The original hotspots identified in the west in 1987 had merged with the newer northern and central hotspots, forming a vast, unified area of near-complete forest removal. Ecologically, this signified the collapse of critical ecosystem services, including carbon sequestration, soil stability, and biodiversity support.

Identification and Pressures on Conservation Refugia

In contrast to degradation hotspots, the analysis also identifies areas that have resisted widespread ecological decline, serving as the last bastions of ecosystem functionality. During the period 1987–2004, the northeastern, eastern, and central forest patches were consistently distinguished as high-NDVI zones (0.6 – 0.8) with corresponding high-biomass values (42.58 – 84.82 t/ha). These areas functioned as critical carbon sinks and biodiversity reservoirs, maintaining ecological stability in a rapidly changing landscape. However, even within this timeframe, signs of pressure were evident, with conservation refugia experiencing a 46.5% reduction in their extent ($-1,000$ km²). This contraction signaled the onset of fragmentation and exposure to anthropogenic pressures that undermined their long-term stability.

Between 2014 and 2024, the contraction and fragmentation of these refugia became much more severe. By 2014, the central refugia had already been reduced to smaller, highly fragmented patches, increasing their susceptibility to edge effects such as tree mortality, invasive species incursion, and fire risk. By 2024, the refugia had been pushed almost exclusively into the southeastern and southern parts of the state, where they

survived largely in steep riparian corridors and less accessible terrains. These remaining patches are now highly isolated and under severe anthropogenic pressure, representing the last vestiges of the region's capacity to provide essential ecosystem services.

Spatial Pattern and Drivers of Hotspot Dynamics

The spatio-temporal dynamics reveal a consistent and predictable pattern of hotspot migration and refugia contraction. The directional trend of degradation indicates an eastward and southeastward expansion of deforestation and land-use change from the original epicenters in the west. This progression reflects a frontier-like exploitation of resources, where new lands are targeted once the earlier zones have been exhausted.

The spatial pattern also aligns strongly with human activity, confirming anthropogenic drivers as the primary forces shaping these changes. Hotspots emerged and expanded in areas of high population density, agricultural suitability, and along accessibility networks such as roads and rivers. Agricultural expansion, unsustainable logging, fuelwood harvesting, and settlement growth were the dominant pressures leading to the collapse of vegetation health and the progressive reduction of biomass and carbon stocks.

Ecologically, the expansion and eventual merging of degradation hotspots have led to the formation of large, contiguous areas of ecological collapse. These “ecological deserts” lack the seed sources needed for natural regeneration, disrupt wildlife corridors, and simplify the landscape into a uniform, low-productivity state. Meanwhile, the fragmentation of conservation refugia reduces their resilience, leaving them increasingly vulnerable to collapse.

The multi-temporal hotspot analysis provides a compelling visual and quantitative assessment of both vulnerability and resilience across the Southern Guinea Savannah of Taraba State. It identifies the western, northwestern, and central zones as persistent degradation hotspots responsible for the majority of ecosystem service losses over the 37-year study period. In contrast, the southeastern zone now stands as the last conservation refugium, whose protection has become a matter of urgent ecological and policy priority.

This spatial prioritization is vital for guiding conservation planning, policy formulation, and the design of restoration programs. It underscores that interventions must be spatially explicit, directed toward halting the eastward expansion of degradation while simultaneously fortifying and protecting the few remaining refugia in the southeast. Without such targeted action, the region risks complete ecological collapse, with devastating implications for biodiversity, carbon sequestration, and local livelihoods.

Relationship Between Degradation Hotspots and Conservation Refugia Across the Study Period (1987–2024)

The comparative trends presented in Table 4 highlight the inverse relationship between degradation hotspots and conservation refugia across the study period (1987–2024). Hotspots, initially confined to the western and southwestern areas, expanded rapidly eastward and northward, eventually consolidating into a dominant contiguous zone by 2024. In parallel, conservation refugia—once extensive across the northeast, east, and central regions—contracted drastically, becoming highly fragmented and restricted to small patches in the southeast.

This dynamic illustrates a landscape-wide ecological shift from resilience to vulnerability, with the near-total collapse of carbon sinks, biodiversity reservoirs, and ecosystem service capacity.

Table 5. Comparative Trends of Degradation Hotspots and Conservation Refugia (1987–2024)

Period	Degradation Hotspots (NDVI: -0.42 to 0.43; Biomass: 0–10.31 t/ha)	Conservation Refugia (NDVI: 0.6–0.8; Biomass: 42.58–84.82 t/ha)
1987	Concentrated in the west and southwest; ~1,850 km ² identified as primary hotspots due to early agricultural expansion and settlement pressures.	Northeastern, eastern, and central forest patches (~2,150 km ²) served as core refugia with high carbon storage and biodiversity.
2004	Hotspots expanded by 56.8% (+1,050 km ²), radiating eastward; degradation corridors emerged along rivers and roads.	Refugia reduced by 46.5% (~1,000 km ²), with fragmentation beginning in central zones.
2014	Intensification of degradation corridors; new hotspots consolidated in central and northern areas; total degraded area exceeded 3,500 km ² .	Severe contraction of central refugia; surviving patches became fragmented and highly vulnerable to edge effects.
2024	Catastrophic consolidation: western, northwestern, and central hotspots merged into a dominant, contiguous degradation zone covering most of the study area.	Refugia confined almost entirely to southeastern and southern riparian corridors (~600 km ²), highly isolated and under intense pressure.

The results of the one-way ANOVA presented in Table 6 show that mean NDVI values differed significantly across the study years ($F = 49.177$, $p < 0.001$). This indicates that vegetation health, measured through greenness and canopy vigor, was not constant over time but underwent statistically meaningful changes between 2004, 2014, and 2024. The between-group variation in NDVI was much greater than the within-group variation, confirming that temporal factors, such as land use intensity and environmental changes, strongly influenced vegetation dynamics in the Southern Guinea Savannah.

Table 6 One-way ANOVA for NDVI Across Years

Variable	Source	Sum of Squares	Df	Mean Square	F	Sig. (p)
NDVI	Between Groups	1.61	2	0.80	49.177	0.000
	Within Groups	57.34	3513	0.016		
	Total	58.94	3515			

To identify where these differences occurred, a Tukey's HSD post hoc test was conducted (Table 7). The results revealed a significant increase in NDVI between 2004 and 2014 (Mean Difference = +0.0383, $p < 0.001$), reflecting a temporary phase of vegetation recovery or regeneration, possibly linked to fallow cycles and localized conservation in riparian areas. However, between 2014 and 2024, NDVI declined sharply (Mean Difference = -0.0501, $p < 0.001$), signifying widespread vegetation degradation and fragmentation consistent with intensified deforestation, agricultural expansion, and fuelwood harvesting in the region.

Tukey's HSD Post Hoc Test for NDVI

Table 7: Tukey's HSD Post Hoc Test for NDVI across Years

Comparison	Mean Difference	p-value	95% CI (Lower-Upper)	Significant (p<0.05)
NDVI_2004 vs 2014	0.0383	0.000	0.0259 – 0.0506	Yes
NDVI_2004 vs 2024	-0.0118	0.0656	-0.0242 – 0.0006	No
NDVI_2014 vs 2024	-0.0501	0.000	-0.0624 – -0.0377	Yes

The comparison between 2004 and 2024 showed no statistically significant difference ($p = 0.066$), suggesting that the temporary gains in vegetation health observed in 2014 were not sustained and that by 2024, the ecosystem had regressed to conditions comparable to those of 2004. Collectively, these results highlight a cyclical pattern of short-term recovery followed by more severe decline, underscoring the dominance of anthropogenic pressures over natural regeneration processes in shaping long-term vegetation health trends in the study area.

Implications

Taken together, the NDVI results highlight that vegetation greenness peaked in 2014 but subsequently regressed by 2024 to levels statistically indistinguishable from those in 2004. This finding mirrors the trajectories of biomass and carbon sequestration, providing convergent evidence of ecosystem decline. The alignment across the three indicators strengthens the conclusion that ecosystem services, particularly primary productivity, carbon storage, and climate regulation, have been significantly compromised by ongoing deforestation and land degradation processes. Furthermore, the close correspondence between biomass, carbon, and NDVI values demonstrates the ecological interdependence of these measures. NDVI effectively captured the vegetation dynamics underlying biomass accumulation and carbon sequestration, validating its use as a reliable remote-sensing proxy for assessing forest condition in the Southern Guinea Savannah zone.

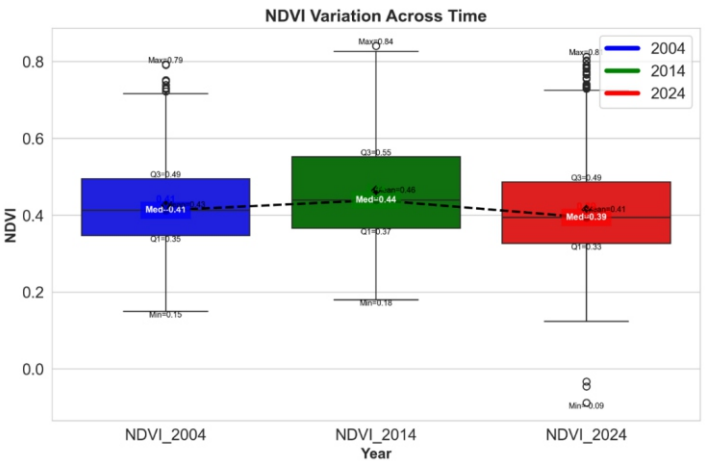


Figure 8: NDVI (Normalized Difference Vegetation Index) Across the Years

The boxplot for NDVI, an index of vegetation greenness and vigor, also follows the same temporal trajectory. In 2004, NDVI values clustered around a median of 0.41, with most sites ranging between 0.35 and 0.49. This suggests a moderate level of vegetation cover and photosynthetic activity at the baseline. By 2014, the median increased to 0.44, with the interquartile range stretching between 0.37 and 0.55. Several high outliers above 0.80 reflected patches of exceptionally healthy vegetation. This improvement corresponds with the biomass and carbon peaks observed in 2014. The Tukey HSD test also confirms a significant increase in NDVI between 2004 and 2014 (+0.038, $p < 0.001$).

In 2024, NDVI declined to a median of 0.39, nearly identical to but slightly lower than 2004. The distribution tightened, but the presence of lower values indicated that many sites lost vegetation vigor, reflecting increased land degradation. The NDVI boxplot, therefore validates the biomass and carbon results, showing a peak in 2014 followed by a reversion to baseline levels in 2024. This highlights the temporary nature of vegetation recovery and the persistence of degradation pressures in the Southern Guinea Savannah.

Discussion of Findings

The findings of this study indicate a progressive and accelerating decline in vegetation health across the Southern Guinea Savannah (SGS) of Taraba State between 1987 and 2024, with dense forest cover contracting from 21.5% of the landscape in 1987 to highly fragmented patches by 2024. The expansion of degradation hotspots from the west and northwest into central and eastern zones underscores the strong influence of agricultural expansion, settlement growth, and resource extraction on vegetation dynamics.

The observed decline in vegetation greenness aligns with previous studies in Nigeria and beyond. For example, Joshua, Ojeh, and Atuma [10] reported a 24% reduction in vegetation cover in the Kurmi Local Government Area of Taraba State between 2010 and 2020, attributing the decline to unsustainable agricultural practices and settlement expansion. This agreement underscores the pervasive nature of anthropogenic pressures across Taraba State and the Guinea Savannah belt.

Similarly, Idisi, Lawal, and Deekor [8] documented long-term reductions in NDVI across South-South Nigeria between 2000 and 2020, identifying both climate variability and land use change as primary drivers. This parallels the present study's conclusion that human activities particularly agriculture and fuelwood extraction are major contributors to vegetation decline in the SGS.

At the broader Nigerian scale, Adepoju, Millington, and Tansey [3] highlighted extensive land use/land cover changes in Lagos driven by urbanization and agricultural expansion. The present study's hotspot analysis, which revealed degradation spreading along road and river corridors, supports their conclusion that accessibility accelerates vegetation loss, suggesting that infrastructure development acts as a spatial catalyst for degradation.

Globally, the findings resonate with Pan et al [6] who identified hidden browning trends within the broader pattern of global greening, particularly in regions where land use intensity undermines natural regeneration. The contraction of conservation refugia in the SGS also mirrors results from Fensholt and Rasmussen [5], who found that vegetation decline in the Sahel was strongly influenced by rainfall variability and unsustainable land management practices.

Despite these consistencies, the results differ from reports of "greening" in parts of West Africa. For instance, Olsson, Eklundh, and Ardö [7] documented a recent greening trend in the Sahel, largely attributed to improved rainfall since the 1980s. Unlike the Sahel, the SGS in Taraba State did not sustain greening despite experiencing periods of regeneration between 2004 and 2014. This discrepancy highlights the overriding role of anthropogenic pressures in the SGS compared to the more climate-driven dynamics of the Sahel.

The temporary NDVI increase between 2004 and 2014 in the SGS partially agrees with the inconsistent greening patterns

reported by Osunmadewa, Wessollek, and Karrasch [9] in the Nigerian Guinea Savannah, where rainfall fluctuations contributed to spatially heterogeneous vegetation outcomes. However, the inability to sustain greening into 2024 suggests that increasing population density, intensified land use, and resource extraction have outweighed potential climatic benefits in the study area.

The findings reinforce the consensus that vegetation health in savannah ecosystems is highly vulnerable to anthropogenic drivers. The expansion and consolidation of degradation hotspots into "ecological deserts" not only reduce biomass and carbon stocks but also threaten biodiversity, watershed stability, and food security. The confinement of conservation refugia to riparian corridors and less accessible southeastern areas underscores the urgency of protecting these remaining strongholds of ecological resilience. This study therefore contributes to the broader body of evidence that calls for immediate interventions such as reforestation, agroforestry, and community-based conservation to safeguard ecosystem services in the SGS and similar ecological zones.

Conclusion

The spatio-temporal analysis of vegetation health in the Southern Guinea Savannah of Taraba State reveals a progressive and alarming trend of ecological degradation between 1987 and 2024. Dense vegetation cores that once stabilized the ecosystem have been systematically reduced, giving way to fragmented and degraded landscapes dominated by cropland and fallow systems. Hotspot analysis shows a clear eastward expansion and consolidation of degradation, while conservation refugia are now restricted to isolated southeastern patches. This trajectory signals a severe erosion of ecosystem services essential for carbon storage, biodiversity conservation, soil fertility, and watershed regulation. If unchecked, the region risks ecological collapse with profound implications for food security and rural livelihoods. Immediate, evidence-based interventions are therefore critical to halt degradation and promote ecological resilience.

Recommendations

Based on the findings of the study, the following recommendations were made:

i. Conservation zoning: The last remaining patches of dense vegetation, mainly in the southeastern and riparian areas, should be designated as conservation zones. Legal protection, community reserves, or forest sanctuaries will safeguard these refugia, which function as biodiversity reservoirs, carbon sinks, and ecological buffers. Without protection, these areas risk further fragmentation and eventual collapse.

ii. Restoration programs: Degraded landscapes, especially in the northwest and central zones, identified as hotspots, require urgent ecological restoration. Approaches such as reforestation, agroforestry, and assisted natural regeneration can rebuild vegetation structure, enhance soil fertility, and restore ecosystem services. Prioritizing restoration in hotspot areas will maximize ecological recovery.

iii. Sustainable land-use planning: Agricultural expansion, fuelwood harvesting, and settlement encroachment are major drivers of vegetation decline. Land-use policies should enforce regulated farming practices, promote energy alternatives to reduce fuelwood dependency, and guide settlements away from

fragile ecosystems. Integrating remote sensing data into planning will improve monitoring and enforcement.

iv. Community engagement: Local communities are central to sustaining vegetation health. Providing incentives for community-based forest management, training in climate-smart agriculture, and awareness campaigns on ecosystem services will enhance participation. Empowering local stakeholders ensures long-term compliance and reduces dependence on unsustainable practices.

v. Policy alignment: Findings should be integrated into Nigeria's commitments under the Sustainable Development Goals (SDGs 13 & 15) and the Great Green Wall Initiative. Aligning regional interventions with these frameworks will attract funding, strengthen policy support, and ensure long-term resilience. Multi-sector collaboration—linking environment, agriculture, and forestry agencies—will be essential for coordinated action.

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