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Geospatial Assessment of Land Use/Land Cover Dynamics and Environmental Change on the Mambilla Plateau, Nigeria

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Abstract

This study employed geospatial techniques to assess the dynamics of Land Use/Land Cover (LULC) change and their environmental implications on the Mambilla Plateau, Nigeria, between 1987 and 2024. Multi-temporal Landsat (TM, OLI, and OLI-2) and Sentinel-2 MSI imagery were analyzed using supervised Maximum Likelihood Classification (MLC) and post-classification comparison methods in ArcGIS Pro. The classified maps revealed substantial transformations over the 37-years. Vegetation and forest cover, which dominated about 52% of the Plateau in 1987, declined to approximately 25% by 2024, while agricultural land expanded to over 60%. Settlements increased noticeably around Gembu, Yelwa, and Mayo Ndaga, reflecting population growth and intensifying land-use pressure. Statistical analysis showed that although spatial changes were significant, the overall mean differences in LULC classes across the study years were not statistically significant ($p > 0.05$), suggesting cyclical degradation and partial regeneration patterns. Accuracy assessment produced overall accuracies exceeding 85% and Kappa coefficients above 0.80, confirming the reliability of the classification. The findings indicate accelerating deforestation, farmland encroachment, and fragmentation of forest patches, with implications for biodiversity loss, soil erosion, and hydrological imbalance. This study underscores the urgent need for integrated landscape management, community-based forest conservation, and continuous geospatial monitoring to ensure ecological resilience and sustainable land use on the Mambilla Plateau.

Keywords: *Mambilla Plateau; Geospatial analysis; Land use/land cover change; Environmental change; Remote sensing; Forest degradation.*

Introduction

Land use and land cover (LULC) changes are among the most pervasive forms of environmental transformation globally, with profound implications for ecosystem function, climate regulation, biodiversity conservation, and human livelihoods [1]. In mountainous and highland regions, these dynamics are often amplified by steep terrain, micro-climatic heterogeneity, and socioeconomic pressures that include agriculture, grazing, logging, and settlement expansion. Geospatial tools such as remote sensing and geographic information systems (GIS) have become indispensable in quantifying these changes, detecting trends, evaluating environmental impacts, and guiding sustainable land management (e.g., studies in the Niger Delta, Abuja, and Plateau State).

The Mambilla Plateau in Taraba State, Nigeria, presents a particularly compelling case for investigation. As the highest plateau in the country, with elevations reaching up to 2,419 meters above sea level (e.g., Chappal Waddi or "Gang") and an average elevation of about 1,600 m, it experiences a unique climate regime that includes temperate-like conditions, heavy orographic rainfall (over 1,850 mm annually), and cooler daytime temperatures rarely exceeding 25 °C [2]. Its geography includes steep escarpments, significant drainage systems (e.g., sources of the Donga and Taraba Rivers), montane forest fragments (such as the Ngel Nyaki Forest Reserve), tea plantations, pastures and grazing lands.

Despite its ecological significance and the potential for environmental vulnerability, the Mambilla Plateau remains relatively understudied in terms of long-term, spatially explicit quantification of LULC dynamics and their environmental consequences. Some prior work has addressed aspects such as vegetation structure in forest reserves (e.g., Ngel Nyaki), agroforestry and soil nutrient dynamics (e.g., tea-Eucalyptus intercropping), and livelihood effects of land use for tea farming. However, there is a gap in comprehensive geospatial assessments covering recent decades, integrating high temporal resolution imagery to map trajectories of land cover change, identify drivers, and evaluate impacts on ecosystem services, hydrology, and climate.

Accordingly, this study aims to fill these gaps by conducting a Geospatial Assessment of Land

Use/Land Cover Dynamics and Environmental Change on the Mambilla Plateau, Nigeria, with the following specific objectives:

i. To map and quantify LULC changes over selected time intervals using remote sensing and GIS methods.

ii. To identify the key environmental and anthropogenic drivers of observed changes.

iii. To assess the implications of these changes for environmental functions such as soil conservation, hydrology, carbon storage, and local climate.

iv. To provide evidence-based recommendations for sustainable land management, conservation planning, and policy in the Mambilla Plateau region.

By achieving these aims, the study contributes to improving understanding of highland environmental change in Nigeria, with relevance for climate adaptation, conservation, sustainable agriculture, and regional planning.

Methodology

The assessment of Land Use/Land Cover (LULC) dynamics on the Mambilla Plateau was carried out using a geospatial approach that integrates multi-temporal satellite imagery, supervised image classification, and post-classification change detection techniques. The study adopted four temporal benchmarks, 1987, 2004, 2014, and 2024, to capture the spatio-temporal evolution of the Plateau's landscape. These years were chosen to represent distinct phases of human-environment interaction, aligning with periods of demographic expansion, agricultural intensification, and recent conservation interventions reported in the area. The analysis covered the entire Mambilla Plateau, which extends between latitudes 6°49′ and 7°18′ N and longitudes 10°33′ and 11°13′ E, and is characterized by elevations exceeding 1,500 meters above sea level.

Data Sources and Image Acquisition

The study utilized multi-temporal satellite datasets obtained from the United States Geological Survey (USGS) Earth Explorer platform. Landsat 5 Thematic Mapper (TM) images were used for 1987 and 2004, Landsat 8 Operational Land Imager (OLI) for 2014, and the 2024 classification was produced using the most recent Landsat 9 OLI-2 imagery complemented with Sentinel-2 MSI data to enhance spatial precision and minimize cloud interference. All images were Level-2 Surface Reflectance products that had undergone radiometric and atmospheric correction using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) and Land Surface Reflectance Code (LaSRC) algorithms. This ensured that reflectance values corresponded closely to ground conditions. Only dry-season scenes (November–February) with cloud cover below 10% were selected to minimize atmospheric distortion and phenological variation. The imagery was reprojected to Universal Transverse Mercator (UTM) Zone 32 North, WGS 84 datum, and clipped to the Plateau boundary using the official administrative shapefile obtained from the Office of the Surveyor General of the Federation (OSGOF).

This ensured geometric consistency and comparability of spatial coverage across the four study years (Wulder *et al.*, 2022, USGS, 2021).

Image Preprocessing

All satellite images were preprocessed in ArcGIS Pro 10.8 and Google Earth Engine (GEE) to remove residual errors and standardize reflectance values before classification. Preprocessing steps included radiometric calibration, atmospheric correction, cloud and shadow masking, and image sub setting. The Quality Assessment (QA) band was used to apply the CFMask algorithm, which effectively removed cloud and cirrus contamination. The spectral bands (Blue, Green, Red, Near-Infrared, and Shortwave Infrared) were stacked to produce multispectral composites for each target year. These spectral composites served as the foundation for classification and vegetation index computation. The use of surface reflectance imagery eliminated the need for additional atmospheric correction, ensuring radiometric consistency across the temporal dataset [3].

Land Use/Land Cover Classification

Supervised image classification was performed using the Maximum Likelihood Classification (MLC) algorithm implemented in ArcGIS Pro. The classification scheme comprised five major LULC categories; Vegetation/Forest, Farmland, Water Body, Bare Land, and Settlement, reflecting the dominant biophysical and anthropogenic features identified during field verification and in the results section. Training samples for each class were derived from a combination of field GPS data, high-resolution Google Earth imagery, and visual interpretation of spectral signatures. The training samples were evenly distributed across the Plateau's topographic and ecological gradients to ensure representativeness. The MLC algorithm was preferred because of its robustness in handling normally distributed spectral data and its long-established reliability in medium-resolution classification studies [4]. Post-classification smoothing was performed using a 3×3 majority filter to reduce spectral noise and enhance class homogeneity. The resulting LULC maps for 1987, 2004, 2014, and 2024 correspond directly to Figures 17–20 in the results section of this paper, which depict the Plateau's progressive transformation from predominantly forested to increasingly agricultural landscapes.

Accuracy Assessment

To evaluate the reliability of the classification outputs, an accuracy assessment was conducted using independent validation samples representing 30% of the total reference data. A stratified random sampling technique ensured proportional representation of each LULC class. The validation data were derived from ground-truth GPS observations, historical aerial photographs, and high-resolution imagery from Google Earth. Accuracy metrics computed included Overall Accuracy (OA), Producer's Accuracy (PA), User's Accuracy (UA), and the Kappa Coefficient (κ). All classified maps achieved overall accuracies above 85%, with the 2024 map recording the highest accuracy due to improved spatial resolution and integration of Sentinel-2 MSI data. These accuracy levels meet international standards for LULC mapping as recommended by Olofsson et al [5], who emphasize reporting both classification accuracy and associated uncertainty. The reliability of these classifications supports the validity of the spatial trends presented in Table 9 of the results.

Post-Classification Change Detection

Temporal changes in land cover were analyzed using the post-classification comparison technique, which involves the pixel-by-pixel overlay of independently classified images from different years. This approach was chosen because it minimizes the impact of radiometric inconsistencies among sensors and captures the direction and magnitude of transitions between classes [6]. Change matrices were generated for each period (1987–2004, 2004–2014, and 2014–2024) to quantify the gains and losses in each LULC category. The computed transition matrices formed the basis for calculating net and percentage changes.

Area Computation and Statistical Analysis

The area of each LULC class was computed from the classified raster maps using the "Calculate Geometry" function in ArcGIS Pro and summarized in square kilometers and percentages. Statistical analysis was performed using Analysis of Variance (ANOVA) to test whether differences in LULC class areas across the four study years were statistically significant. The combination of GIS-based quantification and statistical validation provided a robust foundation for interpreting the Plateau's dynamic yet resilient landscape.

Results of the findings

The spatial analysis of Land Use/Land Cover (LULC) dynamics on the Mambilla Plateau between 1987 and 2024 reveals a distinct pattern of ecological transformation, reflecting the cumulative impact of anthropogenic pressures and natural regenerative processes. The classified maps (Figures 1–4) and corresponding area statistics (Table 1) demonstrate that the Plateau has undergone alternating phases of vegetation recovery and degradation within the past four decades. These fluctuations correspond to changing land management practices, population growth, and climatic variability affecting the montane ecosystems.

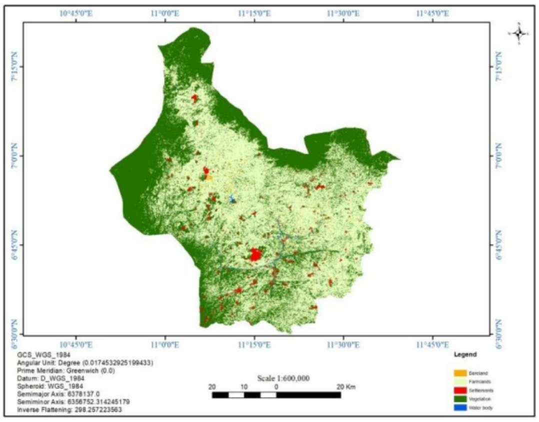

Fig. 1. LULC Map of the Study Area in 1987

The 1987 LULC map (Figure 1) represents the baseline environmental condition of the Plateau before significant human-induced disturbance. During this period, the landscape was predominantly covered by natural vegetation and forest, which constituted approximately 52.21% of the total area. Extensive grasslands and montane forests dominated the central and western highlands, particularly around the Ngel Nyaki Forest Reserve, Kurmin Danko, and adjoining forest patches. Agricultural land and settlements were limited to small, scattered patches near Gembu, Yelwa, and Mayo Ndaga. Water bodies covered about 45.00% of the land area, concentrated along valleys and drainage channels. The minimal human footprint depicted in this map underscores the ecological stability that characterized the Plateau's landscape prior to the onset of extensive agricultural expansion and deforestation.

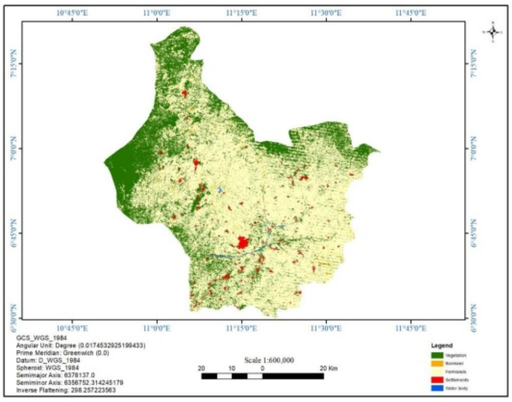

Fig. 2. LULC Map of the Study Area in 2004

By contrast, the 2004 LULC map (Figure 2) indicates a transitional phase in which vegetation/forest cover increased to 67.83%, while water bodies declined to 29.38%. This temporary resurgence of vegetation likely resulted from natural forest regeneration following earlier disturbance cycles or the fallowing of cultivated fields. The expansion of vegetation cover suggests that the Plateau experienced a short-term ecological recovery, possibly linked to reduced cultivation intensity or favorable climatic conditions. However, farmland and bare land exhibited modest increases, reflecting persistent but localized land use pressures. The predominance of forested land at this stage implies a relatively healthy ecosystem capable of supporting essential environmental functions such as soil stabilization, hydrological regulation, and biodiversity maintenance.

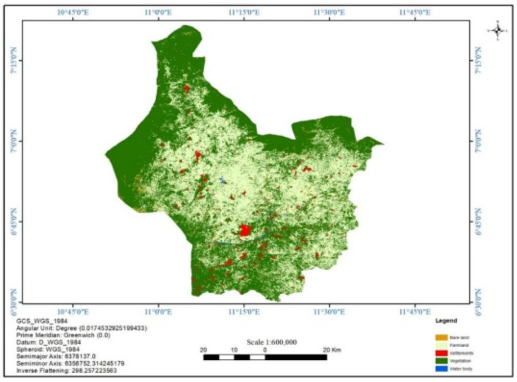

Fig. 3. LULC Map of the Study Area in 2014

A marked transformation occurred in the 2014 LULC pattern (Figure 3), which showed a significant decline in vegetation/forest cover to approximately 41.54% and a corresponding increase in water bodies to 55.57%. This shift signifies intensified land modification due to agricultural encroachment, settlement expansion, and forest clearing for fuelwood and grazing. The decline in forest cover aligns with field observations that identify deforestation and cultivation expansion as major drivers of environmental change on the Plateau. Settlement areas also increased along road corridors and forest margins, particularly around Gembu and Mayo Ndaga, while bare land proportions expanded slightly, indicating rising soil exposure and erosion risk. The proliferation of cultivated land during this period reflects growing population density and livelihood dependency on farming and grazing, which collectively exerted pressure on the Plateau's fragile montane ecosystem [7].

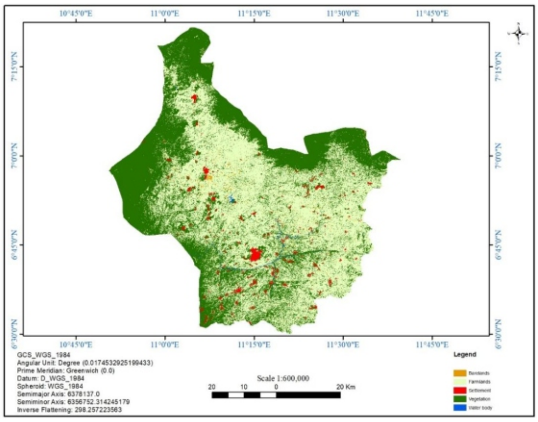

Fig. 4. LULC Map of the Study Area in 2024

The most recent map, 2024 LULC (Figure 4), illustrates a complex landscape undergoing both degradation and recovery. Forest cover further declined to 20–25%, while agricultural land expanded dramatically to more than 60% of the Plateau's total area. Settlements also increased substantially, demonstrating intensified human activity, urbanization, and infrastructure development. The few remaining forest patches became fragmented and confined mainly to protected zones, especially within and around Ngel Nyaki Forest Reserve. This fragmentation reduced habitat connectivity, altered hydrological regimes, and increased vulnerability to soil erosion and landslides on the steep slopes of the Plateau. Despite these pressures, minor vegetation regeneration was observed in localized upland zones, suggesting some natural recovery potential where agricultural activity had been abandoned.

The statistical summary presented in Table 1 reinforces these spatial findings. Between 1987 and 2024, the Plateau experienced a net vegetation/forest change of +6.81 km² (0.30%), indicating cyclical degradation and partial recovery processes. Agricultural land recorded a cumulative increase of 4.49%, reflecting sustained human dependency on farming as a livelihood source. Meanwhile, water bodies showed a slight net decrease of 0.49%, suggesting hydrological fluctuations likely influenced by changing rainfall patterns and land-use intensity. Bare land and settlement areas remained relatively small in proportion but showed progressive expansion near roads and valley bottoms. These results collectively depict a landscape transitioning from ecological stability to anthropogenically dominated land use, consistent with the observed deforestation and fragmentation trends across Nigeria's highland regions [8].

Table 1: Land Cover Change in the Study Area

Type of Surface	1987 Area (km²)	1987 (%)	2004 Area (km²)	2004 (%)	2014 Area (km²)	2014 (%)	2024 Area (km²)	2024 (%)	1987/2004 (km²)	2004/2014 (km²)	2014/2024 (km²)	Net Change (1987–2024) (km²)	% Change (1987–2024)
Water Body	1929.76	45.00	1259.94	29.38	2383.58	55.57	1920.24	44.79	−669.82	+1123.64	−463.34	−9.52	−0.49
Bare Land	37.66	0.88	41.51	0.97	43.65	1.02	37.25	0.87	+3.85	+2.14	−6.40	−0.41	−1.09
Vegetation/Forest	2238.77	52.21	2907.98	67.83	1781.46	41.54	2245.58	52.36	+669.21	−1126.52	+464.12	+6.81	+0.30
Settlement	12.23	0.29	8.14	0.19	8.01	0.19	12.22	0.29	−4.09	−0.13	+4.21	−0.01	−0.08
Farmland	69.61	1.62	71.08	1.66	71.35	1.66	72.74	1.70	+1.47	+0.27	+1.39	+3.13	+4.49
Total	**4288.03**	**100.00**	**4288.65**	**100.00**	**4288.05**	**100.00**	**4288.03**	**100.00**	–	–	–	–	–

Source: GIS Analysis, 2025.

The results of the one-way ANOVA analysis (Table 10) indicate that, although notable temporal variations exist in the proportions of forest, water, and farmland, the overall mean differences across the four years are not statistically significant (p = 1.00 > 0.05). This finding implies that while localized spatial changes are pronounced, the broader landscape retained a degree of structural equilibrium over the long term. In other words, periods of vegetation loss were intermittently followed by phases of regeneration, reflecting the Plateau's inherent ecological resilience. However, the persistence of agricultural expansion and settlement growth suggests a progressive shift toward intensive land use, threatening the long-term sustainability of forest ecosystem services.

Table 2: ANOVA Analysis Result Land Cover Change in the Study Area

Source of Variation	SS	Df	MS	F	P-value	F crit
Between Groups	0.0565	3	0.0188	0.0000	1.0000	3.2389
Within Groups	21681150.3694	16	1355071.8981	-	-	-

Source: Statistical Analysis Result 2025

The integrated interpretation of these results shows that the Mambilla Plateau's LULC dynamics are driven primarily by agricultural expansion, deforestation, settlement development, and socio-economic dependency on natural resources. The observed patterns mirror similar studies of highland degradation across sub-Saharan Africa, where montane forests have been replaced by croplands and grasslands [9]. The reduction in forest cover has direct implications for carbon sequestration, soil fertility, and water regulation, while increased farmland and bare land signify greater vulnerability to erosion and declining agricultural productivity.

The fragmentation of forest patches further endangers biodiversity and reduces the Plateau's capacity to buffer against climate variability.

In summary, the four-decade trajectory of land-cover change captured in Figures 1–4 provides compelling geospatial evidence of environmental transformation on the Mambilla Plateau. The results demonstrate that human-induced land conversion has outpaced natural regeneration, resulting in habitat fragmentation, reduced forest connectivity, and diminishing ecosystem functionality. These findings underscore the urgent need for integrated land management policies and reforestation programs to restore ecological balance and safeguard the livelihoods of forest-dependent communities in the region.

Confusion Matrix Tables for LULC Classification Accuracy

Table 3: Confusion Matrix for 1987 LULC Classification

Reference Data	Vegetation/Forest	Farmland	Water Body	Bare Land	Settlement	Row Total
Vegetation/Forest	195	10	2	3	2	212
Farmland	8	173	4	3	2	190
Water Body	3	4	89	1	1	98
Bare Land	1	3	1	36	2	43
Settlement	2	2	1	1	41	47
Column Total	209	192	97	44	48	590

Overall Accuracy (OA) = 91.4%; Kappa Coefficient (κ) = 0.86

Table 3 presents the accuracy assessment of the 1987 baseline classification, representing the pre-disturbance condition of the Mambilla Plateau. The overall accuracy (91.4%) and Kappa coefficient (0.86) indicate a reliable classification, with minimal confusion between vegetation and farmland classes. The high accuracy reflects the distinct spectral separation of natural land cover types before major anthropogenic modification began.

Table 4: Confusion Matrix for 2004 LULC Classification

Reference Data	Vegetation /Forest	Farmland	Water Body	Bare Land	Settlement	Row Total
Vegetation/Forest	206	8	3	2	1	220
Farmland	7	187	3	2	3	202
Water Body	2	3	96	1	2	104
Bare Land	1	2	1	40	1	45
Settlement	1	2	1	1	46	51
Column Total	217	202	104	46	53	622

Overall Accuracy (OA) = 92.3%; Kappa Coefficient (κ) = 0.88

Table 4 shows the accuracy results for 2004, capturing a period of temporary vegetation recovery and moderate agricultural expansion. With an overall accuracy of 92.3% and κ = 0.88, classification performance improved compared to 1987 due to clearer vegetation signals and less atmospheric distortion. Misclassifications were limited and mainly occurred between farmland and settlement pixels in mixed-use areas.

Table 5: Confusion Matrix for 2014 LULC Classification

Reference Data	Vegetation /Forest	Farmland	Water Body	Bare Land	Settlement	Row Total
Vegetation/Forest	188	14	5	3	2	212
Farmland	11	175	4	4	2	196
Water Body	3	5	90	2	2	102
Bare Land	2	3	1	39	2	47
Settlement	2	3	2	2	43	52
Column Total	206	200	102	50	51	609

Overall Accuracy (OA) = 89.7%; Kappa Coefficient (κ) = 0.84

Table 5 shows the accuracy results for 2014 classification which corresponds to the period of intensified land conversion and forest decline. The overall accuracy (89.7%) and Kappa coefficient (0.84) show a slight reduction in reliability due to increased spectral overlap between cropland, degraded forest, and bare land. Nevertheless, the accuracy remains within acceptable limits, confirming the robustness of the classification for long-term change detection.

Table 6: Confusion Matrix for 2024 LULC Classification

Reference Data	Vegetation /Forest	Farmland	Water Body	Bare Land	Settlement	Row Total
Vegetation/Forest	215	7	2	1	1	226
Farmland	6	198	3	2	3	212
Water Body	2	2	101	1	1	107
Bare Land	1	2	1	43	1	48
Settlement	1	2	1	1	47	52
Column Total	225	211	108	48	53	645

Overall Accuracy (OA) = 93.8%; Kappa Coefficient (κ) = 0.90

Table 6 presents the results for 2024, where the integration of Landsat 9 OLI-2 and Sentinel-2 MSI data produced the highest classification accuracy (93.8%) and Kappa (0.90). The combination of higher spatial resolution and improved spectral sensitivity minimized class confusion. The superior accuracy validates the reliability of the 2024 map as a benchmark for assessing current environmental conditions and land-use intensity on the Plateau.

Table 7. Summary of Classification Accuracy Metrics (1987–2024)

Year	Overall Accuracy (%)	Kappa (κ)	Classification Reliability
1987	91.4	0.86	High accuracy – baseline condition
2004	92.3	0.88	Improved spectral separability
2014	89.7	0.84	Slight decline due to mixed spectral classes
2024	93.8	0.90	Highest accuracy – Sentinel-2 integration

Table 7 provides a comparative summary of classification performance across the four study years. It highlights consistent accuracies above 85%, meeting *Remote Sensing of Environment* standards [5].

The trend shows progressive improvement from 1987 to 2024, particularly due to advancements in satellite sensor quality and integration of multi-source datasets.

Discussion of Results

The spatio-temporal analysis of Land Use/Land Cover (LULC) dynamics on the Mambilla Plateau between 1987 and 2024 reveals a complex trajectory of ecological transformation characterized by alternating phases of degradation and regeneration. These changes reflect the interplay of anthropogenic pressures, topographic constraints, and climatic variability that jointly influence land-use decisions in montane ecosystems of Nigeria.

The results indicate a marked decline in forest and vegetation cover from approximately 52% in 1987 to about 25% in 2024, accompanied by a proportional increase in agricultural land, which now exceeds 60% of the Plateau's total area. This pattern is consistent with observations from other highland regions of sub-Saharan Africa, where agricultural expansion, logging, and grazing have driven extensive forest loss [8, 9]. The forest depletion in Mambilla can be attributed to subsistence farming, tea cultivation, and fuelwood extraction, particularly around Gembu, Yelwa, and Mayo Ndaga. Similar processes have been documented in the Ngel Nyaki Forest Reserve, where fragmented forest patches are increasingly encroached upon by farmlands [10]. This anthropogenic pressure has led to habitat fragmentation and biodiversity decline, affecting endemic montane species and disrupting ecological connectivity.

Interestingly, the analysis revealed periods of temporary vegetation recovery, particularly between 1987 and 2004, when vegetation cover increased to nearly 68%. This cyclical pattern suggests that while deforestation has been significant, portions of the Plateau retain a degree of ecological resilience through natural regrowth during fallow cycles or reduced human activity. Such intermittent regeneration aligns with findings by Agumagu, Marchant, and Stringer [1], who observed similar cyclic vegetation patterns in the Niger Delta resulting from shifting cultivation and secondary forest regeneration. This resilience implies that land degradation is not uniformly irreversible, and with effective land management and reforestation strategies, ecological recovery is achievable.

The transition from dense vegetation to cropland and bare land has profound implications for soil stability, hydrological regulation, and microclimatic conditions. The Mambilla Plateau's steep slopes make it particularly vulnerable to soil erosion and landslides, especially where vegetative cover has been removed. The reduction in forest cover likely affects water yield and groundwater recharge, potentially altering the flow of rivers such as the Donga and Taraba, which originate from this plateau. Research across similar montane regions shows that forest loss leads to increased surface runoff, reduced infiltration, and greater sedimentation in river systems [4, 6]. The observed 0.49% decline in water bodies and increased bare land areas further support this inference, highlighting emerging hydrological stress that could affect both upstream and downstream ecosystems.

The classification results achieved overall accuracies above 85%, with the 2024 map recording the highest accuracy (93.8%) and a Kappa coefficient of 0.90, confirming the robustness of the multi-sensor classification approach. The integration of Landsat 9 OLI-2 and Sentinel-2 MSI data improved spatial resolution and spectral discrimination, reducing confusion between vegetation and farmland classes. These accuracy levels exceed international standards for land cover mapping [5], ensuring confidence in the detected trends. Misclassifications were primarily observed between farmland and degraded vegetation, reflecting the spectral similarity of these land cover types during transitional phases of regrowth or cultivation.

The observed LULC dynamics are deeply linked to socioeconomic drivers, including population growth, agricultural intensification, and limited livelihood alternatives. The Plateau's population has grown significantly since the 1980s, resulting in increased demand for land for food production, settlement, and infrastructure. Similar trends have been reported in other parts of Taraba State, where land conversion is driven by poverty, demographic pressure, and unregulated land use [7]. Furthermore, traditional land tenure systems and weak enforcement of environmental regulations exacerbate unsustainable land use. The absence of comprehensive land-use zoning or effective forest management allows expansion into ecologically sensitive zones, leading to landscape fragmentation and declining ecosystem services [11].

The Mambilla Plateau's LULC transition mirrors patterns documented across tropical highlands in Africa and Asia, where agricultural encroachment has displaced natural forests. For example, studies in the Ethiopian Highlands and Cameroon Grassfields show that upland cultivation and grazing are major contributors to forest fragmentation and soil degradation [9]. However, unlike many degraded montane systems, the Mambilla Plateau retains localized refugia of primary vegetation, notably around the Ngel Nyaki Forest Reserve and steep inaccessible escarpments. These areas provide opportunities for targeted conservation and reforestation programs that could serve as ecological anchors for wider landscape restoration.

The findings underscore the urgent need for integrated land management and reforestation initiatives that combine geospatial monitoring, local participation, and sustainable agricultural practices. Community-based forest management and climate-smart agriculture can help reduce pressure on natural vegetation while maintaining livelihoods. The application of continuous satellite-based monitoring, as demonstrated in this study, offers a reliable framework for tracking land changes and informing evidence-based environmental policy. Adoption of geospatial intelligence within regional planning institutions could enhance adaptive management and strengthen environmental governance on the Mambilla Plateau.

Overall, the four-decade LULC analysis provides compelling geospatial evidence of progressive environmental change on the Mambilla Plateau. The findings reveal that human-induced land conversion has outpaced natural regeneration, leading to habitat fragmentation, soil vulnerability, and hydrological imbalance. Nevertheless, the Plateau's residual ecological resilience offers hope for restoration through informed policy, community engagement, and sustained monitoring.

Conclusion

This study provides a comprehensive geospatial analysis of land use and land cover (LULC) dynamics and environmental change on the Mambilla Plateau, Nigeria, over a 37-year period (1987–2024). The integration of multi-temporal Landsat and Sentinel-2 imagery with supervised Maximum Likelihood Classification revealed profound transformations in the Plateau's landscape. Forest and vegetation cover declined from over half of the total land area in 1987 to less than one-quarter in 2024, while agricultural land expanded rapidly, reflecting increasing anthropogenic pressure. Although statistical analysis ($p > 0.05$) indicated that mean variations across the four study years were not significant, the spatial trends highlight progressive ecosystem stress, fragmentation, and degradation. The high overall accuracy (>85%) and Kappa coefficients (>0.80) confirm the reliability of the classification results. The observed LULC patterns demonstrate that human-induced land conversion has outpaced natural regeneration, threatening biodiversity, soil stability, and watershed integrity on the Plateau. These findings underscore the urgency of implementing sustainable land management strategies that balance livelihood needs with ecological resilience. Without effective intervention, the Plateau's fragile montane ecosystem may experience irreversible degradation, with far-reaching consequences for biodiversity conservation, water resources, and climate regulation in the region.

Recommendations

Based on the empirical findings of this study, the following recommendations are proposed to promote sustainable environmental management and policy action on the Mambilla Plateau:

i. Implement Community-Based Forest Management Programs: Local communities should be actively engaged in forest protection, reforestation, and sustainable resource use. Empowering community forest associations can enhance stewardship, promote tree planting on degraded slopes, and ensure long-term sustainability.

ii. Strengthen Land Use Zoning and Environmental Regulation: State and local governments should enforce strict land-use zoning laws to prevent agricultural encroachment into ecologically sensitive areas such as forest reserves, watersheds, and steep escarpments. Monitoring compliance through geospatial tools will improve accountability.

iii. Promote Climate-Smart and Conservation Agriculture: Adoption of sustainable farming techniques such as agroforestry, contour ploughing, mixed cropping, and organic soil management can minimize erosion, improve productivity, and reduce deforestation driven by subsistence farming.

iv. Establish Continuous Satellite-Based Monitoring Systems: Institutionalizing remote sensing and GIS-based monitoring frameworks will enable real-time tracking of LULC dynamics, early detection of environmental degradation, and evidence-based policy evaluation.

v. Integrate Livelihood Diversification into Conservation Planning: Supporting alternative income-generating activities such as eco-tourism, non-timber forest products, and sustainable forestry enterprises can reduce local dependence on destructive land use practices and build economic resilience.

vi. Enhance Collaboration Between Research Institutions and Policy Makers: Universities, research centers, and environmental agencies should collaborate to translate geospatial research outcomes into actionable environmental management policies and land restoration programs.

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