



ЭКОЛОГИЯ ECOLOGY


DOI: 10.22363/2313-2310-2026-34-2-205-222

EDN: PKLJEW

UDC 581.5

Research article / Научная статья

Multi-Scale Landscape Responses of Vegetation to Urban Growth in Makurdi, Nigeria

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Abstract. Rapid urban expansion is reshaping landscapes across Sub-Saharan Africa, but its effects on vegetation structure remain underexplored. This study examines vegetation responses to urban growth in Makurdi, Nigeria, from 2000–2025, using land-use/land-cover analysis and landscape metrics. Urban intensity zones were delineated to account for spatial variability of anthropogenic impact, and vegetation structure was assessed at class and landscape levels with FRAGSTATS. The results show extensive growth in development accompanied by vegetation decline and fragmentation. Low-intensity zones retained cohesion, while moderate-intensity zones experienced the greatest fragmentation and loss of dominance, indicating their high vulnerability. High-intensity zones remained degraded, with small, isolated remnants. The landscape metrics further reveal increasing fragmentation, edge complexity, and heterogeneity, alongside declining cohesion. These findings highlight scale-dependent vegetation responses and demonstrate the value of configuration-based metrics for ecological insight. The multi-scale framework provides a robust basis for urban planning aimed at conserving vegetation integrity in rapidly growing African cities.

Keywords: vegetation fragmentation, landscape metrics, urban intensity zones

Authors' contribution. *O. Shaibu* — conceptualization, conducting research, preparing a manuscript. *A.A. Kirichuk* — methodology, final version of the manuscript. All authors have read and approved the final version of the manuscript.

Conflicts of interest. The authors declare no conflicts of interest.

Statement on the use of artificial intelligence technologies. No generative artificial intelligence technologies were used in the creation of this article.

Data availability. All data obtained during this study are included in the published article.

Article history: received 22.01.2026; revised 15.02.2026; accepted 26.02.2026.

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For citation: Shaibu O, Kirichuk AA. Multi-scale landscape responses of vegetation to urban growth in Makurdi, Nigeria. *RUDN Journal of Ecology and Life Safety*. 2026;34(2):205–222. <http://doi.org/10.22363/2313-2310-2026-34-2-205-222> EDN: PKLJEW

Многомасштабные ландшафтные реакции растительности на рост городов в Макурди, Нигерия

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Аннотация. Быстрое расширение городов меняет ландшафты по всей Африке к югу от Сахары, однако его влияние на структуру растительности остается недостаточно изученным. Авторами изучены реакции растительности на рост городов в Макурди, Нигерия, в период с 2000 по 2025 г. с использованием анализа землепользования/землепокpытия и ландшафтных метрик. Выделены зоны интенсивности урбанизации для учета пространственной изменчивости антропогенного воздействия, а структура растительности оценивалась на уровне классов и ландшафтов с помощью FRAGSTATS. Результаты показывают обширный рост застройки, сопровождающийся сокращением и фрагментацией растительности. Зоны низкой интенсивности сохранили целостность, в то время как зоны средней интенсивности испытали наибольшую фрагментацию и потерю доминирования, что указывает на их высокую уязвимость. Зоны высокой интенсивности оставались деградированными, с небольшими изолированными остатками. Ландшафтные метрики дополнительно показывают усиление фрагментации, сложности границ и неоднородности наряду со снижением связности. Эти результаты подчеркивают зависимость реакции растительности от масштаба и демонстрируют ценность метрик, основанных на конфигурации, для экологического анализа. Многомасштабная структура обеспечивает надежную основу для городского планирования, направленного на сохранение целостности растительности в быстрорастущих африканских городах.

Ключевые слова: фрагментация растительности, ландшафтные метрики, зоны городской интенсивности

Вклад авторов. *Шаibu О.* — разработка концепции, проведение исследования, подготовка рукописи. *Киричук А.А.* — методология, разработка концепции, окончательная версия рукописи. Все авторы ознакомлены с окончательной версией статьи и одобрили ее.

Заявление о конфликте интересов. Авторы заявляют об отсутствии конфликта интересов.

Заявление об использовании технологий искусственного интеллекта. При создании настоящей статьи технологии генеративного искусственного интеллекта не использовались.

Заявление о доступности данных. Все данные, полученные в ходе этого исследования, включены в опубликованную статью.

История статьи: поступила в редакцию 22.01.2026; доработана после рецензирования 15.02.2026; принята к публикации 26.02.2026.

Для цитирования: *Shaibu O., Kirichuk A.A.* Multi-scale landscape responses of vegetation to urban growth in Makurdi, Nigeria // Вестник Российского университета дружбы народов. Серия: Экология и безопасность жизнедеятельности. 2026. Т. 34. № 2. С. 205–222. <http://doi.org/10.22363/2313-2310-2026-34-2-205-222> EDN: PKLJEW

Introduction

Urbanization is a defining global trend of the 21st century, reshaping land-use patterns and undermining natural habitats [1; 2]. Expanding built environments displace vegetation, intensifying fragmentation and reducing ecological resilience [1; 3]. These impacts are most severe in rapidly developing regions where urban growth often outpaces conservation planning [3; 4], producing heterogeneous landscapes with degraded vegetation and diminished ecosystem services [5; 6]. Urban vegetation supports biodiversity, regulates microclimates, and sustains green infrastructure [7–9]. Yet, habitat conversion disrupts spatial configurations, creating fragmented mosaics of isolated patches with reduced connectivity and heightened edge effects, threatening species persistence [10–13]. Thus, fragmentation and heterogeneity are critical indicators of urban ecological health, reflecting both quantitative vegetation loss and qualitative degradation of spatial patterns [14; 15].

Assessing these dynamics requires integrating remote sensing with landscape metrics. Remote sensing enables multi-temporal land-use/land-cover (LULC) mapping, while metrics quantify patch size, connectivity, and configuration [16; 17]. Urban growth typically increases patch isolation, reduces mean patch area, and elevates edge density, signaling ecological vulnerability [18]. Standardized metrics such as Percentage of Landscape (PLAND), Number of Patches (NP), Edge Density (ED), and Contagion (CONTAG) via FRAGSTATS provide robust measures of structural complexity [16].

Despite global applications, multi-scale analyses remain scarce in Sub-Saharan Africa, where medium-sized cities experience some of the fastest growth rates [19]. Studies in Malawi and Accra highlight vegetation decline and fragmentation but often rely on isolated metrics or lack gradient-based approaches [20; 21]. Consequently, little is known about how vegetation structure varies along urbanization gradients or how multi-scale patterns emerge from specific growth processes [22; 23]. In cities such as Makurdi, rapid expansion continues without systematic evaluation of vegetation responses. The absence of advanced landscape ecology frameworks limits ecological assessments and biodiversity integration into urban planning [24]. To address this gap, we examine vegetation dynamics in Makurdi (2000–2025) using night-time light (NTL) gradients and FRAGSTATS metrics across urban, peri-urban, and rural zones. This multi-scale approach expands the geographic and methodological scope of urban ecology and provides a data-driven foundation for planning strategies that balance growth with ecological sustainability.

Materials and methods

Study Area Description

This study focuses on Makurdi, the administrative capital of Benue State, Nigeria, located between latitudes 7°38'N–7°50'N and longitudes 8°24'E–8°48'E (see Figure 1). The city lies within the Benue Trough at an elevation of 93–105 m above sea level and is bisected by the Benue River, its dominant hydrological landmark [25]. Makurdi falls within the Southern Guinea Savanna zone, characterized by a sub-humid tropical climate (Köppen Aw) with mean annual rainfall of 1,250–1,500 mm [26]. Natural vegetation includes gallery forests along riverbanks and deciduous savanna woodlands with species such as *Azelia africana* and *Daniellia oliveri* [27].

Between 2000 and 2025, Makurdi has grown into a major regional hub linking Nigeria’s southeastern and northern corridors. Its strategic location and role as a state capital have driven rapid population growth and spatial expansion exceeding 4% annually.¹ Urban development is dominated by unplanned horizontal sprawl, converting fertile floodplains and upland woodlands into residential and commercial areas [28]. This expansion has produced a fragmented landscape where built-up areas increasingly encroach on ecologically sensitive wetlands, making Makurdi a critical case for assessing long-term impacts of urbanization on vegetation integrity [28; 29].

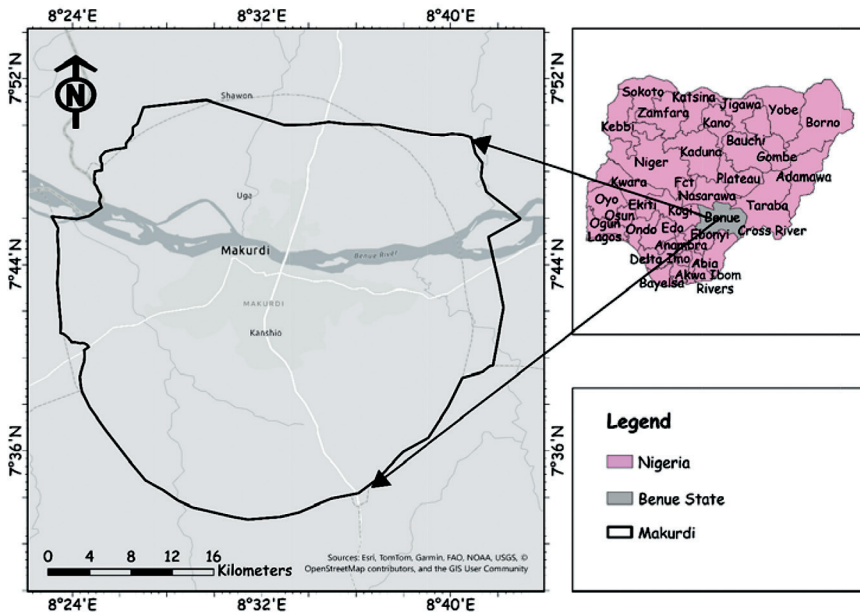


Figure 1. Study Area Map

Source: compiled by O. Shaibu, A.A. Kirichuk.

¹ United Nations. World Population Prospects. Available from: <https://population.un.org/wpp/> (accessed: 09.02.2026).

Analytical Framework and Study Design

This study employs an integrated framework combining land-cover mapping, landscape pattern analysis, and urban intensity modeling to assess vegetation responses across multiple spatial scales. By linking class- and landscape-level metrics with urban pressure gradients derived from night-time light data, the approach captures both localized fragmentation and broader landscape restructuring driven by urban expansion. A multi-scale zonal design was adopted to improve interpretability and provide a robust basis for evaluating how vegetation reorganizes under increasing anthropogenic influence. The conceptual framework is presented in Figure 2, while detailed procedural steps are outlined in Figure 3.

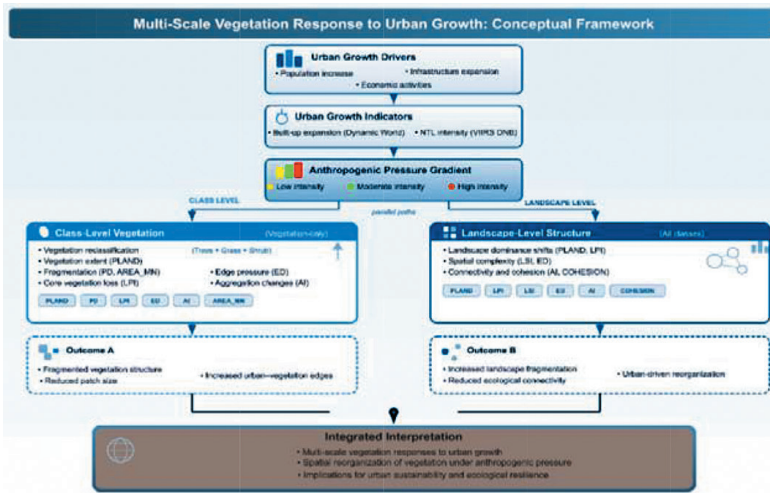


Figure 2. Conceptual Framework

Source: compiled by O. Shaibu, A.A. Kirichuk.

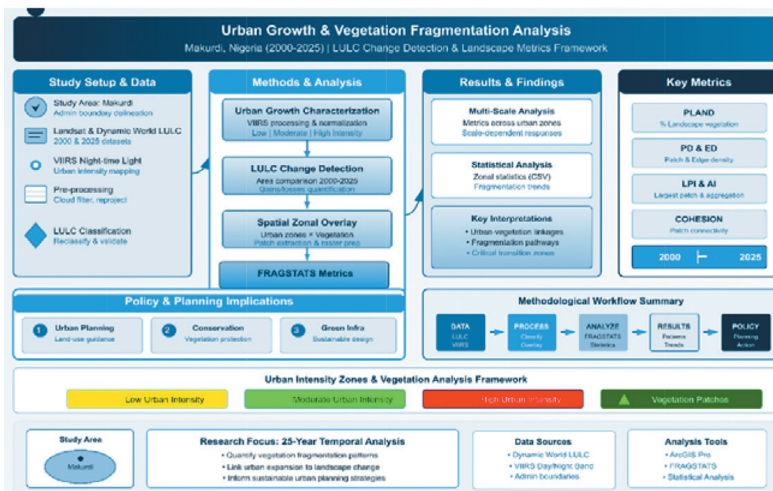


Figure 3. Flowchart of Methodological Framework

Source: compiled by O. Shaibu, A.A. Kirichuk.

Data Acquisition and Pre-processing

We integrated multi-source geospatial datasets spanning 25 years to capture land-cover dynamics and urban intensity. Contemporary LULC data (2025) were derived from the Dynamic World V1 dataset using Sentinel-2 imagery (10 m resolution), while baseline data (2000) were manually classified in ArcGIS Pro from high-resolution historical imagery to ensure consistency. Night-time light (NTL) data from VIIRS Day/Night Band annual composites provided cloud-filtered radiance values as proxies for urban activity and infrastructure expansion. Administrative boundaries defined the study extent, and all datasets were projected to a common coordinate system and resampled to uniform resolution. Nearest-neighbor resampling preserved categorical integrity for LULC data.

Land-Use/Land-Cover Classification and Change Detection

We applied supervised classification to delineate five classes: built-up, vegetation, agriculture, bare land, and water. For 2000 data, a Random Forest (RF) classifier was used in ArcGIS Pro due to its robustness with complex remote sensing datasets. Accuracy was assessed via confusion matrices, overall accuracy, and Kappa coefficients. Post-classification comparison generated LULC transition matrices, enabling computation of per-class area changes and annual transformation rates. This approach aligns with established methodologies for urban change analysis in rapidly expanding African cities [30–32].

Vegetation Reclassification and Raster Preparation

To emphasize ecological processes, LULC classes were reclassified into vegetation (trees, grass, shrubs) and non-vegetation (built-up, bare land, water) groups [33; 34]. Binary vegetation rasters for 2000 and 2025 served as inputs for class-level analysis, while original multi-class rasters supported landscape-level assessments. All rasters were exported as 16-bit signed integer GeoTIFFs to meet FRAGSTATS requirements, ensuring consistent spatial extent and precise cell alignment.

Urban Growth Intensity Assessment

Urban growth intensity was quantified using NTL radiance as a proxy for settlement density and infrastructure. Annual NTL composites were clipped to Makurdi's boundary to generate continuous illumination surfaces. Radiance values were classified into low, moderate, and high-intensity zones using percentile thresholds, following established methods [35–38]. This avoided arbitrary classification and ensured categories reflected relative human activity. Validation through visual comparison confirmed alignment with built-up patterns and peri-urban expansion.

Linking Vegetation Structure to Urban Growth Intensity

We employed a zonal analysis linking vegetation metrics to urban intensity gradients. Vegetation rasters (2000 and 2025) were masked by low, moderate, and high-intensity zones, and FRAGSTATS was applied separately to each. This enabled computation of class-level metrics within distinct urban environments, allowing vegetation change to be interpreted as a differentiated response to anthropogenic pressure rather than a simple temporal shift. The framework provided a process-driven perspective on landscape reorganization.

Multi-Scale Landscape Metric Analysis

Landscape pattern analysis was conducted at both class and landscape levels using FRAGSTATS [39; 40].

- Class-level (vegetation only):
 - Extent: Percentage of Landscape (PLAND);
 - Fragmentation: Patch Density (PD);
 - Dominance: Largest Patch Index (LPI);
 - Edge effects: Edge Density (ED);
 - Connectivity: Mean Patch Area (AREA_MN), Aggregation Index (AI)
- Landscape-level (all LULC classes):
 - Fragmentation & dominance: PD, LPI;
 - Boundary complexity: ED, Landscape Shape Index (LSI);
 - Connectivity: Cohesion Index (COHESION), AI.

By integrating vegetation-specific metrics with systemic indicators, this multi-scale framework captured scale-dependent responses, linking localized vegetation loss to broader urban-driven transformations.

Results

Land Use/Land Cover Change Results

Table 1 summarizes LULC distribution in Makurdi between 2000 and 2025. The results reveal a marked landscape reorganization, with divergent trends across major land-cover classes. Vegetation remained dominant but declined from 77.5% in 2000 to 71.8% in 2025, highlighting mounting pressure on natural and semi-natural ecosystems. Built-up land expanded substantially, increasing from 103.10 km² (11.6%) to 146.60 km² (16.5%), reflecting rapid urban growth and intensifying anthropogenic influence. Cropland also rose moderately to 59.80 km², indicating agricultural expansion alongside urbanization. Water bodies showed a slight increase to 3.7%, while bare land remained stable at 1.3%.

Overall, urban expansion and the redistribution of vegetated land emerged as the primary drivers of change. These area-based shifts provide essential context for subsequent analyses of spatial configuration and fragmentation. Figure 4 illustrates the spatial distribution of these transformations across the study area.

Table 1. Land-Use/Land-Cover Distribution and Changes in Makurdi, 2000–2025

LULC ID	LULC Class	Area 2000, km ²	Share 2000, %	Area 2025, km ²	Share 2025, %
1	Waterbody	30.40	3.40	33.30	3.70
2	Vegetation	689.60	77.50	638.90	71.80
3	Cropland	54.80	6.20	59.80	6.70
4	Bareland	11.80	1.30	11.30	1.30
5	Built-up	103.10	11.60	146.60	16.50

Note: Percentages represent proportional coverage of the total study area.

Source: compiled by O. Shaibu, A.A. Kirichuk.

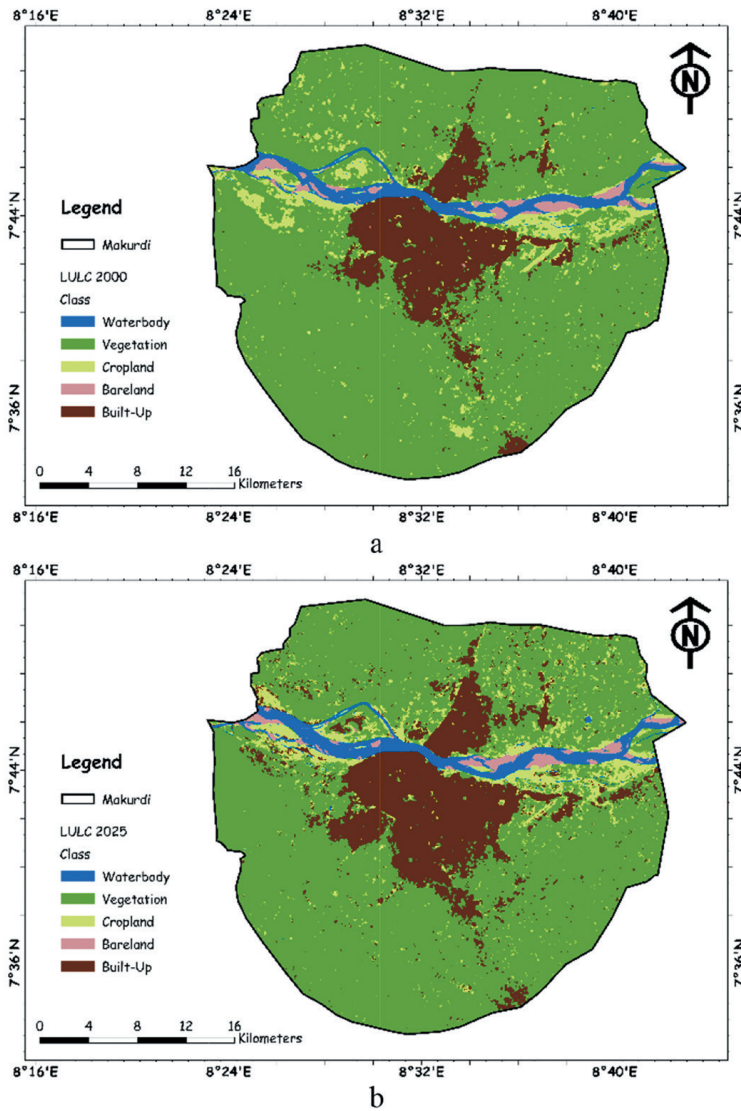


Figure 4. Spatio-temporal patterns of land-use/land-cover in Makurdi showing (a) the 2000 and (b) the 2025 LULC maps, highlighting urban expansion and associated landscape transformation across the study area

Source: compiled by O. Shaibu, A.A. Kirichuk.

Class-Level Vegetation Responses across Urban Intensity Zones

Vegetation metrics were categorized by urban intensity zones to assess structural responses under varying human pressure (Table 2). Results show clear contrasts across low, moderate, and high-intensity areas in both 2000 and 2025.

In low-intensity zones, vegetation occupied a large share of the landscape, with low patch density, strong dominance of the largest patches, and high aggregation. These conditions reflect cohesive vegetation structures in areas with limited anthropogenic disturbance. In moderate-intensity zones, vegetation declined substantially, with smaller, more numerous, and less aggregated patches. This fragmentation indicates transitional landscapes where urban expansion and natural cover coexist, underscoring the vulnerability of these buffer zones to ongoing land-use change. In high-intensity zones, vegetation was minimal, highly fragmented, and weakly aggregated, with negligible dominance. Remaining vegetation persisted only as small, isolated remnants embedded within a built-up matrix, highlighting the severe impact of dense urbanization on spatial integrity.

Table 2. Vegetation Landscape Metrics Across Urbanization Gradients in Makurdi for 2000 and 2025

Urbanization Gradient	Year	PLAND, %	PD, patches/ha	LPI, %	ED, m/ha	AREA_MN, m	AI, %
Low Intensity	2000	53.56	0.0032	34.73	2.94	16,614.53	95.35
	2025	51.68	0.0032	33.63	3.86	16,030.26	93.06
Moderate Intensity	2000	5.46	0.0153	3.49	1.93	356.71	62.79
	2025	3.75	0.0250	1.39	1.59	150.09	54.90
High Intensity	2000	0.46	0.0145	0.09	0.34	31.87	18.60
	2025	0.27	0.0081	0.09	0.19	33.99	25.00

Note. PLAND = Percentage of Landscape, %; PD = Patch Density (number of patches per hectare); LPI = Largest Patch Index, %; ED = Edge Density (m/ha); AREA_MN = Mean Patch Area, m ; AI = Aggregation Index, %. Metrics describe vegetation structure and spatial configuration across urbanization gradients.

Source: compiled by O. Shaibu, A.A. Kirichuk.

Temporal Changes in Vegetation Structure within Urban Intensity Zones

Comparisons of class-level metrics between 2000 and 2025 (Table 2) reveal distinct temporal responses to urban expansion. In low-intensity zones, vegetation remained largely stable, though slight declines in Aggregation Index (AI) and mean patch size (AREA_MN) suggest gradual fragmentation. Despite these subtle shifts, vegetation maintained a cohesive spatial arrangement. In moderate-intensity zones, vegetation exhibited the most pronounced changes. Between 2000 and 2025, dominance and aggregation declined sharply, while fragmentation intensified. These results identify moderate zones as critical ecological interfaces, highly sensitive to urban growth and vulnerable to structural reorganization. In high-intensity zones, vegetation showed little temporal variation. Already severely fragmented by 2000, these areas remained degraded, with persistently low dominance and weak aggregation. This stability reflects conditions where urban pressure had already surpassed thresholds necessary for maintaining coherent vegetation structures prior to the baseline year.

Landscape-Level Spatial Structure Dynamics

Landscape-level metrics (Table 3) highlight systemic restructuring between 2000 and 2025. Patch density increased, indicating progressive subdivision of the landscape into smaller units and a shift from a continuous matrix to a segmented mosaic. The Largest Patch Index (LPI) declined, reflecting reduced dominance of large patches and greater influence of smaller, fragmented units. Concurrently, landscape shape complexity increased, with more irregular boundaries and heightened heterogeneity. Rising edge density further underscores the growing complexity of interactions between adjacent land-cover types.

Connectivity metrics showed slight declines, suggesting marginal weakening of cohesion and aggregation. Although values remained relatively high, the downward trend indicates that expanding anthropogenic land uses are beginning to disrupt regional continuity. Collectively, these findings demonstrate that by 2025, Makurdi’s landscape had transitioned toward a fragmented, heterogeneous structure. This system-wide reorganization provides essential context for the vegetation-level fragmentation patterns identified earlier.

Table 3. Landscape-Level Metrics for Makurdi LULC Structure in 2000 and 2025

Year	PD, patches/100 ha	LPI, %	ED, m/ha	LSI (–)	COHESION, %	AI, %
2000	0.96	39.63	8.93	8.79	99.93	99.58
2025	4.75	36.97	17.97	16.68	99.92	99.13

Note. PD = Patch Density; LPI = Largest Patch Index; ED = Edge Density; LSI = Landscape Shape Index; COHESION = Patch Cohesion Index; AI = Aggregation Index. PD is expressed as number of patches per 100 ha, ED as meters per hectare, LPI and AI as percentages, while LSI is dimensionless.

Source: compiled by O. Shaibu, A.A. Kirichuk.

Integrated Multi-Scale Interpretation of Results

Across both class- and landscape-level analyses, vegetation responses to urban growth in Makurdi proved scale-dependent and spatially differentiated. Landscape metrics revealed a general increase in fragmentation and complexity, while class-level results showed these changes were most acute in moderate and high-intensity zones. Our findings emphasize that area-based assessments alone cannot capture the full extent of vegetation transformation. Configuration shifts fragmentation, dominance, and aggregation offer deeper insight into how vegetation reorganizes under urban pressure. The zonal framework highlights that degradation intensifies along the urbanization gradient, confirming that urban growth in Makurdi is a heterogeneous process with varying ecological impacts across the urban–rural continuum.

Discussion

Result Discussion

In this study, we investigated the multi-scale responses of vegetation to urban growth in Makurdi, Nigeria, over a twenty-five-year trajectory (2000–2025). By integrating LULC transitions with landscape metrics and urban intensity gradients,

our results offer compelling evidence that the structural integrity of Makurdi's vegetation has been compromised by urban expansion, specifically within moderate and high-intensity zones. The nuanced fragmentation patterns identified here reflect broader ecological and urban dynamics documented in other rapidly urbanizing regions of Sub-Saharan Africa and beyond.

Our analysis of landscape composition (see Table 1) revealed a consistent decline in vegetation proportion alongside a sharp increase in built-up areas. This trend aligns with findings from other Nigerian cities, where accelerated urban sprawl has led to the substantial depletion of ecological assets, including natural vegetation and open green spaces [41–43]. Similar declines in vegetation and rising fragmentation have been observed across Nigeria's rainforest and Guinea savanna regions as urban footprints expand, underscores the pervasive influence of urbanization on West African natural landscapes [43; 44].

At the class level, our results demonstrate that vegetation structure becomes increasingly fragmented as urban intensity rises (see Table 2). The elevated patch density and reduced aggregation in these zones suggest that urban development has systematically disrupted the spatial coherence of vegetated land. Such structural responses are consistent with urban greenness fragmentation patterns observed globally, where rising patch density and edge effects follow the subdivision of green space due to sprawl [45–48]. These trends are ecologically significant, as they are frequently linked to reduced habitat connectivity, biodiversity loss, and impaired ecosystem functioning [46; 47; 49].

The observed increase in system-wide fragmentation (see Table 3) further supports the interpretation that Makurdi's overall spatial structure has become more complex and heterogeneous. Metrics such as patch density, edge density, and the landscape shape index all of which reflect landscape subdivision and boundary irregularity increased from 2000 to 2025. Literature suggests these changes indicate a transition toward landscapes where anthropogenic uses prevail at the expense of natural continuity. For instance, studies have highlighted that increases in patch density and shape complexity typically accompany neighborhood expansion, creating mosaic landscapes with diminished ecological cohesion [50–52].

Connectivity-related metrics, including cohesion and aggregation, showed subtle declines, suggesting a gradual weakening of landscape continuity. This shift carries substantive ecological implications; fragmentation-induced reductions in connectivity can hinder species dispersal and compromise ecological resilience. These consequences are well-documented in landscape ecology, where diminished connectivity is associated with compromised ecosystem services and the reduced long-term viability of urban vegetation patches [53–55].

By integrating urban intensity gradients, we gained additional insight into the spatial heterogeneity of these responses. Vegetation in low-intensity zones remained comparatively cohesive, indicating that areas with limited anthropogenic pressure

retain their structural integrity despite broader regional changes. Conversely, moderate and high-intensity zones exhibited severe fragmentation, reflecting the differential impacts of urbanization based on human influence levels. This finding reinforces the necessity of considering spatial heterogeneity in ecological assessments, as global metrics alone may obscure localized responses to anthropogenic pressure.

In the Sub-Saharan African context, urbanization is often characterized by rapid, unplanned expansion that exerts immense pressure on natural environments [56–59]. The patterns we observed in Makurdi mirror these regional trends, highlighting how urban growth reshapes both cover composition and spatial configuration. Furthermore, our multi-scale approach underscores that urban ecological assessments are most informative when they synthesize class-specific responses with overall landscape reorganization.

Limitation of the Study

Despite offering a comprehensive multi-scale assessment, this study has several limitations. First, reliance on two temporal snapshots (2000 and 2025) restricts detection of intermediate or non-linear dynamics, though imagery availability and cloud cover often constrain finer sampling in tropical regions. Second, landscape metrics, while informative, do not directly measure ecological functions such as species richness or habitat quality. Future work should integrate field-based data and higher-resolution environmental indicators.

Additionally, night-time light gradients, though robust proxies for anthropogenic pressure, may not fully capture socio-economic drivers such as land tenure or policy influences. Finally, landscape metrics are sensitive to classification accuracy and resolution; however, these concerns were mitigated through careful reclassification, zonal analysis, and multi-scale integration.

Policy and Urban-Planning Implications

The differentiated vegetation responses observed provide critical guidance for urban planning in Makurdi and similar Sub-Saharan cities. Moderate-intensity zones, where fragmentation is most severe, represent key intervention spaces. Policies should prioritize regulating land conversion, integrating green buffers, and protecting vegetation before thresholds are surpassed.

In low-intensity zones, cohesive vegetation can be preserved through zoning that discourages leapfrog development and promotes compact growth. High-intensity zones require ecological restoration urban parks, street trees, and riparian corridor protection to reconnect fragmented patches and sustain ecosystem services.

More broadly, embedding landscape metrics into routine monitoring and municipal planning offers a powerful tool for balancing development with ecological sustainability. By moving beyond area-based indicators, planners can evaluate the structural health of green spaces and design strategies that enhance resilience in rapidly urbanizing contexts.

Conclusion

This study examined LULC dynamics and vegetation responses to urban growth in Makurdi (2000–2025) using a multi-scale landscape metrics framework. Findings show that urban expansion has driven both a measurable decline in vegetation extent and a profound reorganization of its spatial configuration. While built-up growth and green cover loss highlight anthropogenic influence, configuration-based metrics fragmentation, dominance, and aggregation provide deeper insight into vegetation system responses.

Class-level analysis revealed spatial differentiation along the urbanization gradient: vegetation in low-intensity zones remained cohesive, moderate zones showed the greatest structural sensitivity with accelerating fragmentation, and high-intensity zones reflected persistent degradation. At the landscape scale, rising patch density, edge complexity, and shape irregularity indicate a shift toward a fragmented, heterogeneous mosaic, while declining connectivity suggests weakening cohesion under continued sprawl.

Overall, vegetation degradation in Makurdi is a scale-dependent, spatially heterogeneous process. By identifying zones most vulnerable to fragmentation, this study provides a robust evidence base for integrating green infrastructure conservation into urban planning frameworks across rapidly growing Sub-Saharan African cities.

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