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Predictive Modelling of Land Use Dynamics in Enugu, Nigeria: Evidence from Multi-temporal Remote Sensing Data

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Abstract

This study examines land use dynamics in Enugu, Nigeria, utilizing multi-temporal remote sensing and Geographic Information System (GIS) data to analyze urban expansion from 2003 to 2023. With urban growth outpacing regulatory controls, Enugu exemplifies the challenges of rapid, unmanaged urbanization in mid-sized cities within developing regions. Employing the Urban Expansion Intensity Index (UEII) and Shannon's Entropy, the study reveals a deceleration in expansion intensity, coupled with a persistent pattern of uncontrolled spatial dispersion. Findings indicate a 49.91% increase in urban area from 2003 to 2013, slowing to 19.69% from 2013 to 2023, suggesting limited regulatory impact on peripheral expansion. Classification accuracy metrics validate the reliability of the data, with Kappa values consistently showing high agreement. The results highlight critical implications for urban planning, emphasizing the need for stronger regulatory frameworks and sustainable land use practices. The study advocates for the integration of GIS-based monitoring into urban governance to mitigate the impacts of urban sprawl and ensure environmental resilience. The findings contribute to theoretical urban growth models by showcasing the influence of socio-economic drivers and regulatory inadequacies on land use transitions. This research informs policymakers and urban planners, offering practical tools and policy recommendations for fostering sustainable development in rapidly urbanizing regions like Enugu.

Keywords: Land Use Dynamics, Multi-Temporal Analysis, Sustainable Development, Urban Expansion

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1. Introduction

Urban growth and land use dynamics are critical topics in contemporary urban planning and environmental management. Globally, rapid urbanization and population increase have placed unprecedented pressure on existing land uses, triggering significant conversions to meet emerging demands. The World Bank (2023) notes that more than half of the world's population now resides in urban areas, a trend projected to accelerate in the coming decades. This demographic shift poses substantial challenges for city planners, policymakers, and governments, especially in developing countries where infrastructure and governance systems often lag behind the pace of urban expansion.

Enugu, located in southeastern Nigeria, exemplifies these challenges. The city has experienced considerable population growth driven by rural-urban migration and economic development (Anierobi & Obasi, 2021; Idoko & Ezeodili, 2021). As a result, land use in Enugu has undergone dramatic changes, with agricultural areas and natural landscapes increasingly converted to residential, commercial, and industrial uses. This transformation is not only altering the physical landscape but also impacting the socio-economic and environmental stability of the region. Citing the implication of this transformation, Battpista & Vollaro (2017) aver that the emergence of impervious surfaces and the reduction of vegetation contribute to ecosystem degradation, increased urban heat, and compromised air and water quality.

In response, remote sensing and GIS technologies have been instrumental in monitoring these changes and assessing their implications. The results of this monitoring have highlighted a consistent decrease in forested and grassland areas, with concurrent increases in built-up and bare land (Kanchan et al., 2024; Pijanowski, 2014). Such findings underscore the multifaceted nature of urban growth, which is often spontaneous and unsystematic, leading to unplanned consequences that strain resources and undermine sustainability. Within this context, the urban expansion of Enugu raises pressing questions: What are the specific land use changes occurring within the city? What factors are driving these changes, and at what rate? How do these trends impact sustainable development and environmental resilience?

Despite the existence of urban planning regulations, uncontrolled growth persists, often resulting in inefficient land use, social inequalities, and environmental degradation (Efobi, 2021). This imbalance between development and conservation reflects a pattern common in many rapidly urbanizing regions of Nigeria and underscores the urgent need for evidence-based strategies to manage growth effectively (Ayeni et al., 2023). Thus, the study of land use dynamics in Enugu, leveraging multi-temporal remote sensing data, is essential to understand the spatial and temporal patterns of change. The research, anchored on an empirical examination of land use dynamics in Enugu, seeks to generate actionable insights that can inform the development of sustainable land use allocation frameworks, facilitate efficient resource utilization, and alleviate the adverse environmental repercussions associated with unmanaged land use transformations.

1.1 Research Questions

1. How have temporal variations manifested in the land use patterns of Enugu between 2003 and 2023?
2. What factors have influenced these land use changes in Enugu, and to what extent?
3. What are the projected spatial patterns of land use change and urban growth in Enugu?

1.2 Justification of the Study

The rapid pace of urbanization in Enugu has brought about significant challenges that require in-depth analysis and strategic intervention. This study is justified by the urgent need to address the implications of urban expansion on land use, environmental sustainability, and socio-economic well-being. The findings will be valuable to urban and regional planners, policymakers, investors, and environmental stakeholders seeking to understand the drivers and consequences of land use changes. Accordingly, employing multi-temporal remote sensing data will provide an empirical basis for more informed decision-making and policy development. The study's findings have broader implications for the trajectory of urban growth in Nigeria and other developing regions, thereby contributing to the advancement of more informed and adaptive urban planning practices.

2. Review of Related Literature

The phenomenon of urban growth refers to the expansion of urban areas in terms of population and physical infrastructure. This process is typically driven by factors such as rural-to-urban migration, natural population growth, and economic development (Liu et al., 2022). In agreement, scholars like Turok and McGranahan (2019) emphasize that it results in increased pressure on existing land use, leading to significant shifts in land cover and urban form. The concept of land use dynamics, on the other hand, pertains to the continuous transformation in how land is utilized, influenced by socio-economic and environmental drivers. Pijanowski (2014) highlights that this includes shifts from agricultural to urban or industrial uses, which contribute to changes in ecosystem services and local biodiversity.

Remote sensing refers to the use of satellite or aerial imagery to collect data about the Earth's surface, while GIS (Geographic Information System) is a tool for mapping, analyzing, and managing spatial data. According to Li and Gong (2016), these technologies are pivotal for monitoring land use changes and informing urban planning policies, as they provide accurate, multi-temporal analyses of land cover transitions. It aids in addressing urban sprawl which is defined as the uncontrolled expansion of urban areas into peripheral rural land, characterized by low-density and car-dependent development (Yasin et al., 2021). Surya (2021) identifies urban sprawl as a significant factor contributing to environmental degradation and inefficient land use. Enugu's urban expansion exemplifies these issues, as documented in local urban studies.

Multi-temporal analysis involves examining data from multiple time periods to detect trends and changes over time. Zhai et al. (2021) stress that such analysis is crucial for understanding land use patterns and making predictions about future urban growth. It also aids in sustainability planning, which in the context of urban development, refers to practices that meet current urban growth needs without compromising the ability of future generations to meet theirs (Satterthwaite, 2021). The United Nations (2018) framework advocates for balanced approaches that integrate social, economic, and environmental considerations.

On the other hand, land cover refers to the physical material present on the Earth's surface, such as vegetation, buildings, and water bodies. Changes in land cover are often indicative of underlying land use changes, driven by human activities like construction and deforestation (Selassie et al., 2015). Spatial patterns describe the arrangement and distribution of land uses and features across a geographic area. Studies such as those by Wang et al. (2022) show that analyzing spatial patterns can reveal insights into urban growth trends and their implications for infrastructure and environmental management. Furthermore, environmental degradation is

the decline in environmental quality due to human-induced factors such as pollution, deforestation, and urban sprawl. Battpista and Vollaro (2017) argue that rapid urban growth, if unchecked, exacerbates environmental challenges, contributing to climate change and loss of biodiversity.

2.1 Theoretical Framework

The theoretical framework for this study is rooted in urban growth and land use change theories that help explain the spatial and temporal transformations occurring in Enugu. First is the Central Place Theory (Christaller, 1933) which postulates that urban areas develop as central hubs providing services to surrounding regions. Enugu's growth can be viewed through this lens, as it serves as a focal point for economic activities, influencing land use changes in its periphery. Also, the distribution and accessibility of services contribute to urban expansion and changing land use patterns.

Another is the Bid-Rent Theory (Alonso, 1964) which explains the spatial organization of land use based on economic activities and their competition for proximity to central business districts (CBD). In the context of Enugu, land closer to the city centre is highly valued for commercial and residential purposes, leading to a shift from agricultural to urban land use as demand increases. The Urban Ecology Theory emphasizes the interaction between social and environmental factors in shaping urban development (Grimm et al., 2008). It views cities as ecosystems where competition for resources results in land use changes. The dynamic growth in Enugu can be seen as a process influenced by the push and pull of population growth, resource allocation, and economic opportunities.

The pertinence of the Multiple Nuclei Model (Harris & Ullman, 1945) to the study lies in its suggestion that cities grow around multiple centres or nuclei rather than a single central district. From this perspective, Enugu's urban expansion aligns with this theory as it has developed multiple growth centres, including commercial, residential, and industrial hubs, leading to diverse land use patterns. To what extent does this expansion constitute urban sprawl? Providing an explanation, the Urban Sprawl Theory (Gottmann, 1961) examines the outward spread of urban areas into adjacent rural lands, characterized by low-density development. Enugu's expansion into previously rural areas highlights challenges of urban sprawl, including inefficient land use, environmental degradation, and increased demand for infrastructure.\

These theories provide a robust framework for understanding the complex interactions driving land use changes in Enugu. They help contextualize the empirical findings from remote sensing data and offer insight into the socio-economic and environmental factors that influence urban growth. Therefore, the study aims to contribute to the broader discourse on sustainable urban development and strategic land use planning with an integration of these theoretical perspectives.

2.2 Methodological Framework

The methodological approaches employed in the study of land use dynamics have evolved significantly, particularly with the advent of advanced remote sensing technologies and GIS. Remote sensing has become a cornerstone due to its ability to provide spatially extensive and temporally consistent data (Macarringue et al., 2022). This has culminated in the use of multi-temporal satellite imagery, such as Landsat, Sentinel, and MODIS, has been widely used to monitor land use changes over time (Afira & Wijayanto, 2022).

However, debates persist regarding the trade-offs between spatial, temporal, and spectral resolutions. While high-resolution imagery offers detailed insights, it often comes with higher costs and computational demands, limiting its accessibility for studies in developing regions like Nigeria (Taiwo, et al., 2024). Furthermore, the integration of open-access satellite data with ground-truthing techniques, such as field surveys and participatory mapping, remains underexplored in many African contexts, creating a gap in the validation of remote sensing data.

Analytical methods for land use change detection range from traditional techniques, such as post-classification comparison and change vector analysis, to more advanced machine learning algorithms, including random forests and convolutional neural networks (CNNs). While these machine learning approaches have shown promise in handling complex and non-linear land use patterns (Aljeri, 2023), their application in regions with limited historical data, such as Enugu, Nigeria, is still nascent. Additionally, the lack of standardized protocols for model selection and parameterization often leads to inconsistencies in results, raising questions about the reproducibility of findings across different geographic contexts (Kedron et al., 2021). This makes an appreciation of the contextual background of the case study area crucial.

2.3 Contextual Background

Understanding the contextual background of land use dynamics in Enugu, Nigeria, is essential for situating the

study within the broader socio-economic and environmental landscape. Enugu, historically known as the "Coal City," has undergone significant land use transformations due to urbanization, mining activities, and agricultural expansion. Studies have documented the rapid conversion of forested and agricultural lands into built-up areas, driven by population growth and economic development (Nnaji et al., 2022; Odoh et al., 2024). However, there is a paucity of studies that systematically quantify these changes using multi-temporal remote sensing data. This gap limits the ability to establish baseline trends and assess the long-term impacts of land use changes in the region.

Furthermore, the drivers of land use change in Enugu are multifaceted, encompassing socio-economic, political, and environmental factors (Ibimilua & Ayiti, 2024). Rapid urbanization, fueled by rural-urban migration, has led to the proliferation of informal settlements and the encroachment of built-up areas into ecologically sensitive zones (Nnaji et al., 2022). Additionally, the legacy of coal mining has left behind degraded lands, further exacerbating environmental challenges. While existing studies have identified these drivers, there is limited research on their interplay and relative contributions to land use dynamics. This gap hinders the development of targeted interventions to mitigate the adverse effects of land use changes.

Additionally, the policy and regulatory framework governing land use in Enugu is characterized by fragmented institutions and weak enforcement mechanisms. Despite the existence of urban planning policies, their implementation has been hampered by corruption, inadequate funding, and a lack of community engagement (Echendu, 2023). This highlights the need for evidence-based policymaking that integrates scientific insights from remote sensing and predictive modelling. However, the disconnect between research and policy remains a significant barrier (Ewurum et al., 2020), underscoring the need for studies that bridge this gap by providing actionable recommendations for sustainable land use management.

2.4 Empirical Perspectives

Several empirical studies have explored urban growth, land use dynamics, and the use of remote sensing and GIS technologies in monitoring these changes. Pijanowski et al. (2014) demonstrated the significant reduction in forested areas and the expansion of urban settlements over time, emphasizing the critical role of remote sensing in identifying these changes. Their work underscored the importance of understanding land use transitions and their implications for local ecosystems and planning.

Li and Gong (2016) highlighted the advantages of combining remote sensing with GIS for multi-temporal analyses, providing precise data for evaluating land use changes. Their findings affirmed that these technologies are essential for decision-makers to visualize and quantify shifts in land cover, but noted limitations related to data availability and scale that can constrain broader applications.

Studies specific to African cities, such as Zubair (2020), focused on the impacts of rapid urban expansion on environmental sustainability. Research showed a consistent trend of unregulated urban sprawl leading to habitat loss, inefficient land use, and socio-economic disparities. However, these studies often pointed out a lack of comprehensive long-term data, which can limit the understanding of change trajectories over decades.

Wang et al. (2022) conducted spatial pattern analyses to examine how urban growth patterns affect infrastructure and urban resilience. Their results indicated that while urban growth can stimulate economic opportunities, it poses challenges such as increased demand for services and environmental pressures. They highlighted that few studies integrate predictive modelling with empirical data for future land use projections, leaving a critical gap in sustainable urban planning research.

Selassie et al. (2015) focused on the implications of land cover changes, showing how deforestation and increased impervious surfaces contributed to adverse climatic and hydrological impacts. Despite their contributions, many studies, including theirs, did not specifically address smaller urban centers in developing countries, where data are often fragmented or scarce.

While existing studies have provided insights into the broader trends of urban growth and land use dynamics, there is a distinct lack of localized research addressing mid-sized urban centers such as Enugu. The methodological and contextual gaps identified in the literature justify the need for this study. Firstly, the limited application of advanced remote sensing and machine learning techniques in the Nigerian context highlights the potential for innovative approaches to enhance the accuracy and reliability of land use change detection and predictive modelling.

Secondly, the lack of longitudinal studies on land use dynamics in Enugu underscores the importance of leveraging multi-temporal remote sensing data to establish baseline trends and inform future projections. Finally,

the disconnect between research and policy emphasizes the need for studies that not only generate scientific insights but also provide practical recommendations for sustainable land use management. This study aims to fill these gaps by employing a multi-temporal approach to assess the patterns and drivers of land use change in Enugu over two decades. It also seeks to provide actionable insights that can guide sustainable urban development tailored to the context of Nigerian cities.

3. Methodology

This study adopts a case study research design, focusing on Enugu as a representative mid-sized urban center in Nigeria. The case study approach allows for an in-depth exploration of land use dynamics, supported by empirical data and comparative analysis across different time periods. The design facilitates a detailed understanding of local drivers of urban expansion and their implications for sustainable development.

Enugu, located in southeastern Nigeria, serves as the capital of Enugu State and is a major urban center with significant socio-economic and administrative importance. The city is geographically positioned within the tropical rainforest region, featuring undulating terrain with hills and valleys. The city's population has seen considerable growth, influenced by rural-to-urban migration and expanding economic activities, which have driven substantial land use changes.

The study utilizes multi-temporal remote sensing data sourced from ArcGIS Geographic Information System (GIS) and observation of land uses and urban growth in each of the areas chosen. A mixed-methods approach was employed to gather secondary data from the designated study areas. As an observational study, data collection relied on in-situ observations and interpretations of spatial patterns. Additionally, archival data was obtained from the Ministry of Lands and Urban Development, Enugu, specifically regarding approved layouts, building plans, and land-use conversions within the three Local Government Areas, covering a specified time period.

Furthermore, supplementary data was sourced from the Enugu State Housing Development Corporation, focusing on residential estates within the same Local Government Areas over a defined timeframe. The data encompasses different spectral bands suitable for analyzing land cover changes. Additionally, Geographic Information System (GIS) datasets were incorporated to provide spatial context and enhance mapping accuracy. The temporal range ensures a comprehensive analysis of land use changes over two decades.

The collected data underwent both descriptive and inferential analyses to unravel the underlying patterns and relationships. Descriptive statistics were employed to summarize and visualize the spatial data through various formats, including charts, tables, photographs, and pictorial maps, thereby providing a comprehensive overview of the data. Furthermore, inferential statistics were utilized to investigate the relationships between urban growth and the factors influencing land-use changes. Specifically, a correlational analysis was conducted to examine the pairwise relationships between these variables, with the aim of identifying statistically significant associations and shedding light on the underlying dynamics driving land-use transformations.

4. Results

The study provides a spatiotemporal analysis of urban expansion in Enugu metropolis over three time periods: 2003, 2013, and 2023. The following imageries in Figures 1 to 4 provide a visual illustration of the land use dynamics in Enugu metropolis over a 10-year interval, spanning from 2003 to 2023 as indicated earlier. The essence is for an accurate assessment of the spatial and temporal trends in land use changes as a basis for providing valuable insights into the urbanization processes and land use shifts in the study area through land use dynamics prediction modelling.

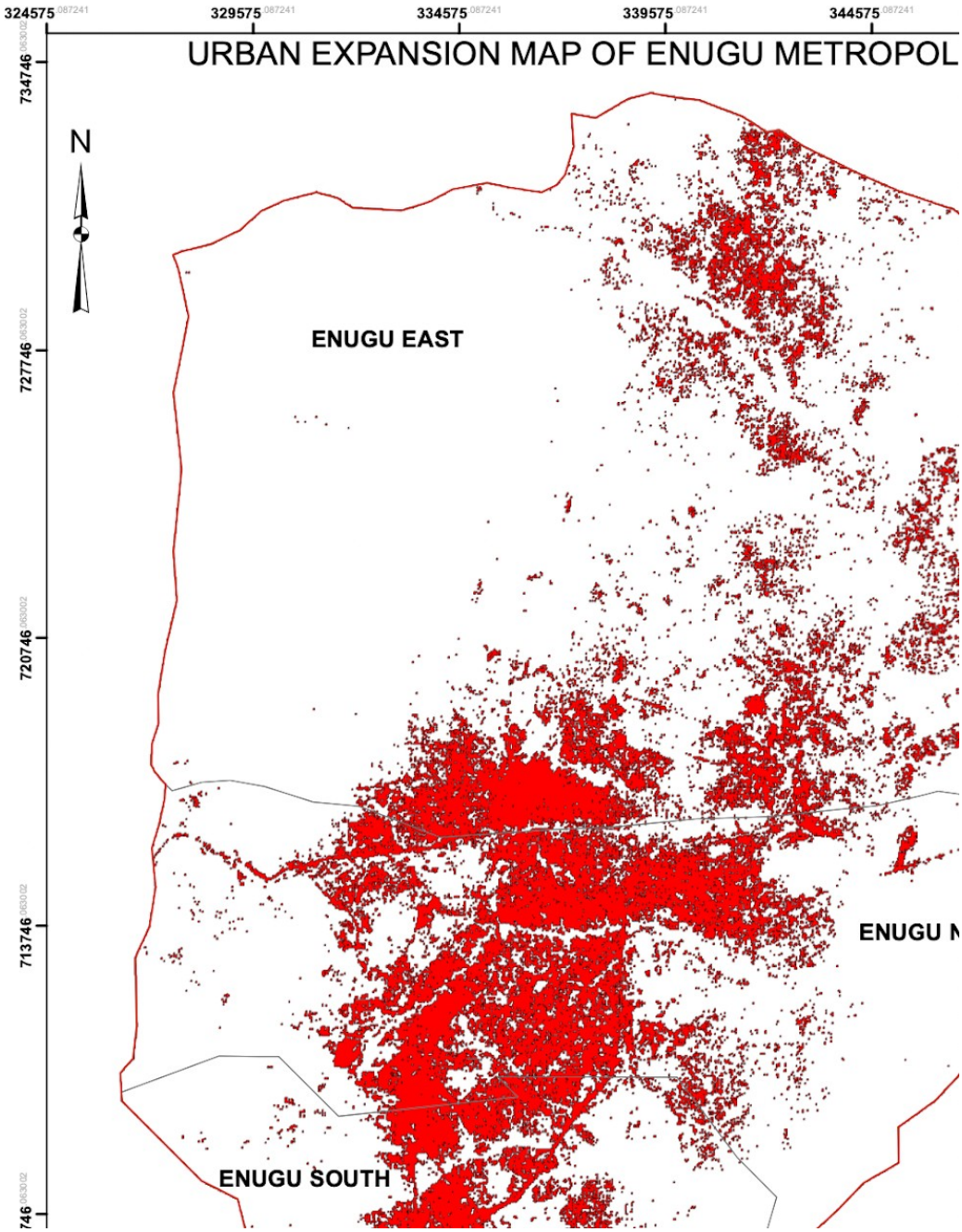


Figure 1: GIS representation of Urban Expansion 2003

Source: Field Survey, 2023

Figure 1 depicts the urban expansion map of Enugu Metropolis in 2003, highlighting the spatial distribution of urban and non-urban areas. The map reveals significant urbanization, particularly in Enugu East and Enugu North, indicating rapid land use changes driven by population growth and economic activities. The spatial patterns suggest a concentration of urban expansion in specific zones, likely influenced by infrastructure development and accessibility.

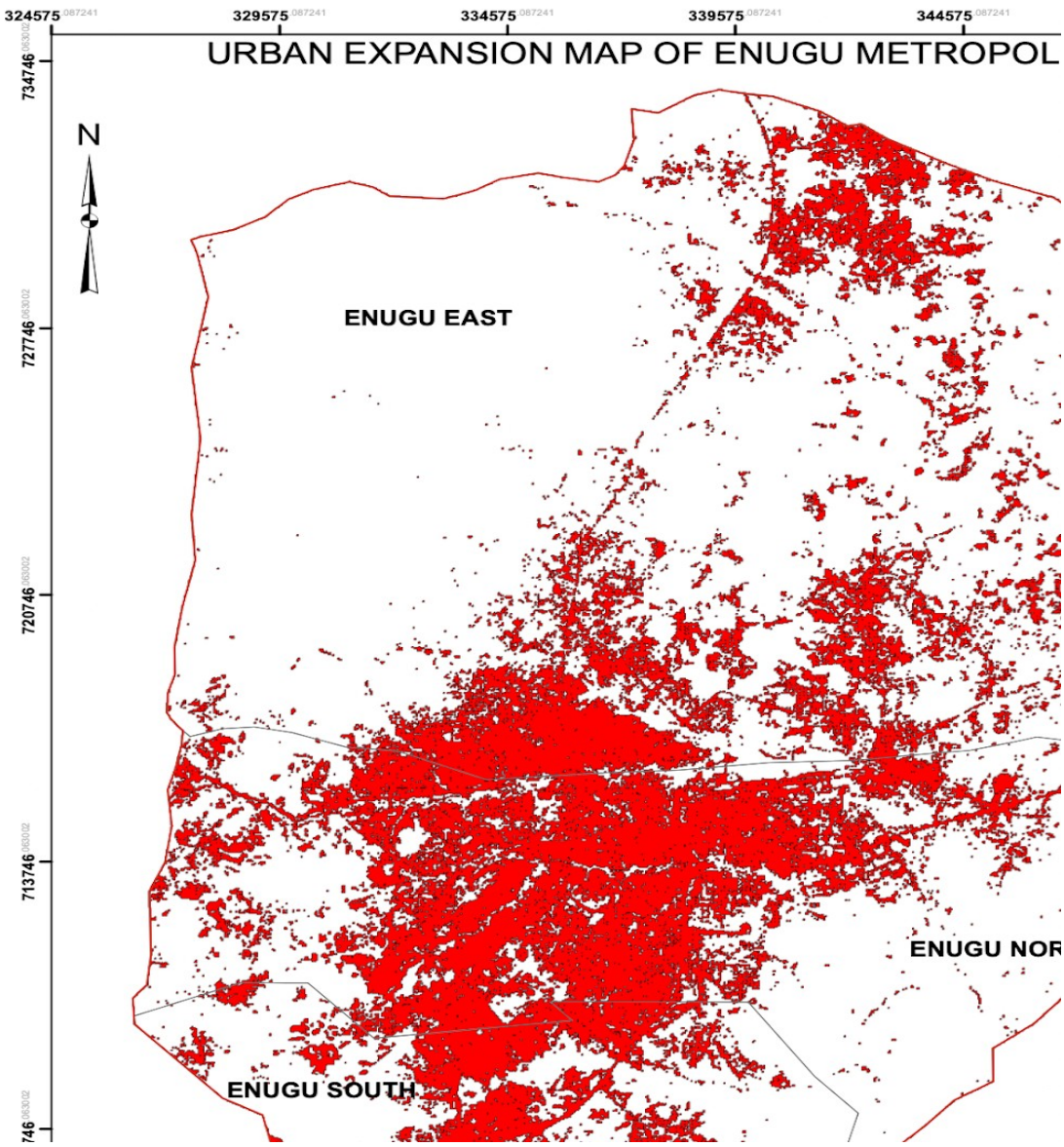


Figure 2: GIS representation of Urban Expansion 2013

Source: Field Survey, 2023

Figure 2 shows the urban expansion map of Enugu Metropolis in 2013, demonstrating a notable increase in urbanized areas compared to the 2003 map, particularly in Enugu East. The expansion indicates a continuation of urbanization trends, likely driven by population growth, economic development, and infrastructural improvements. The spatial distribution of urban areas suggests a pattern of outward growth from the city center, potentially encroaching on previously non-urban zones.

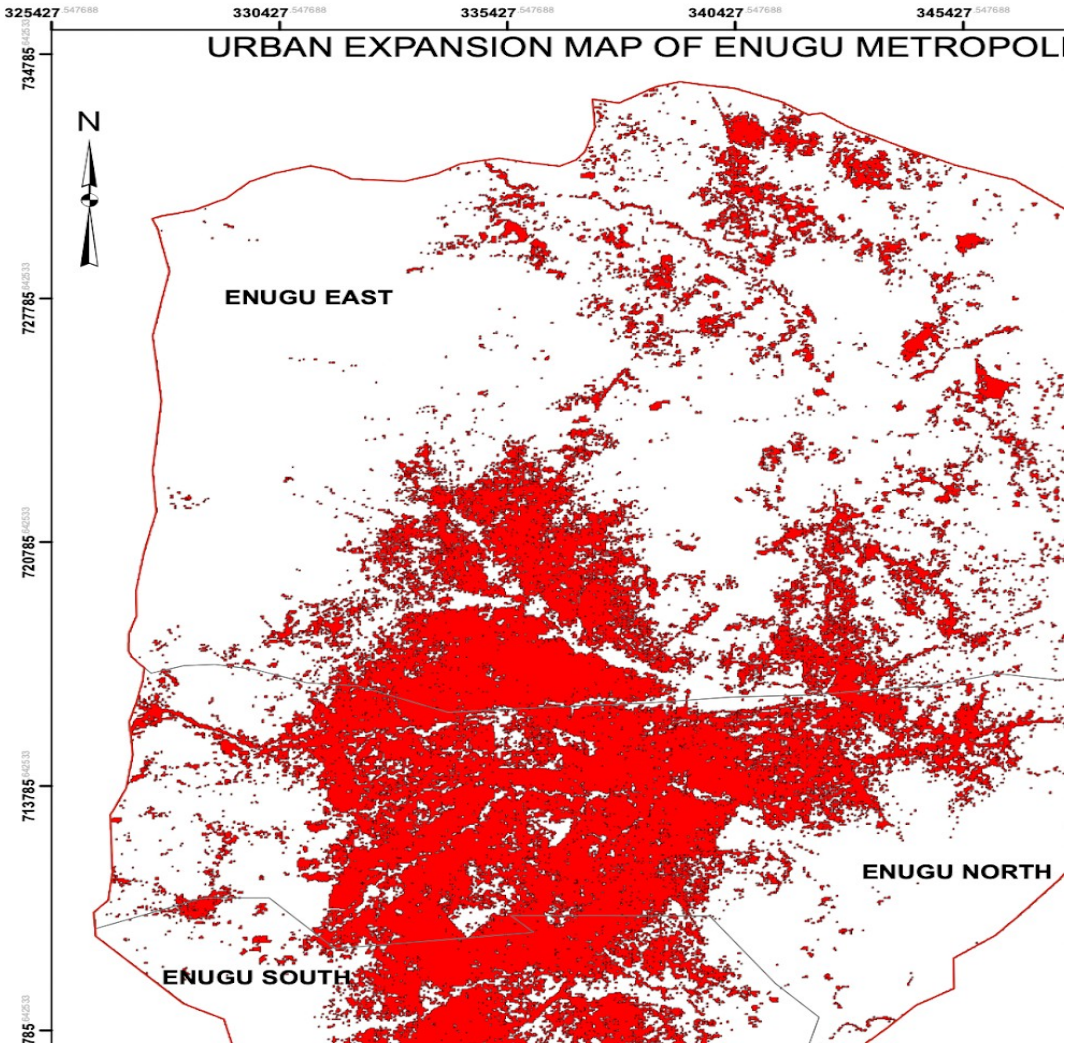


Figure 3: GIS representation of Urban Expansion 2023

Source: Field Survey, 2023

Figure 3 indicates that the 2023 urban expansion map of Enugu Metropolis illustrates a significant increase in urbanized areas compared to previous years, indicating accelerated urbanization. The expansion is particularly evident in Enugu East and surrounding regions, reflecting ongoing population growth and economic activities. The spatial patterns suggest a continued outward spread from the city center, potentially impacting previously non-urban and ecologically sensitive areas.

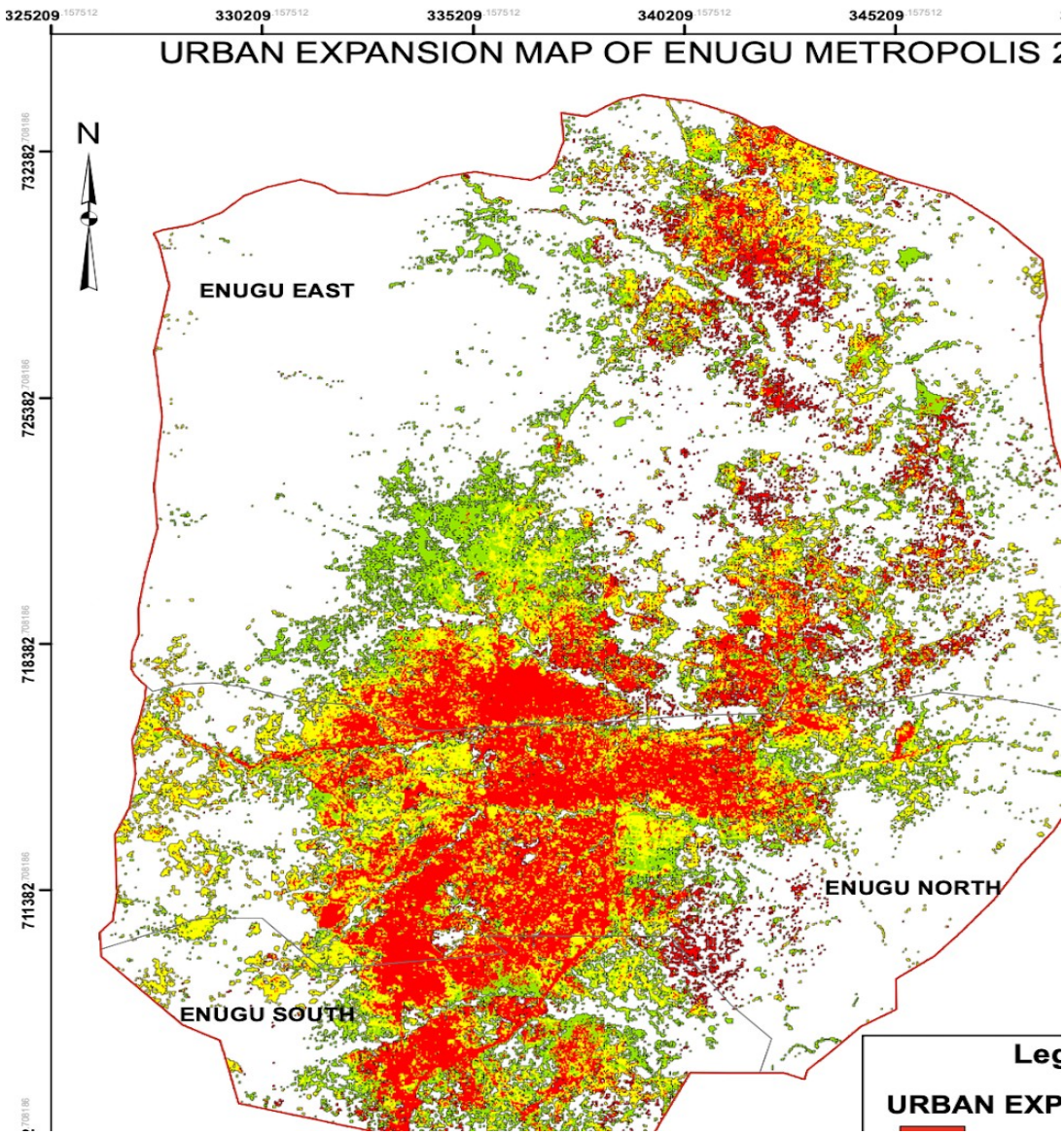


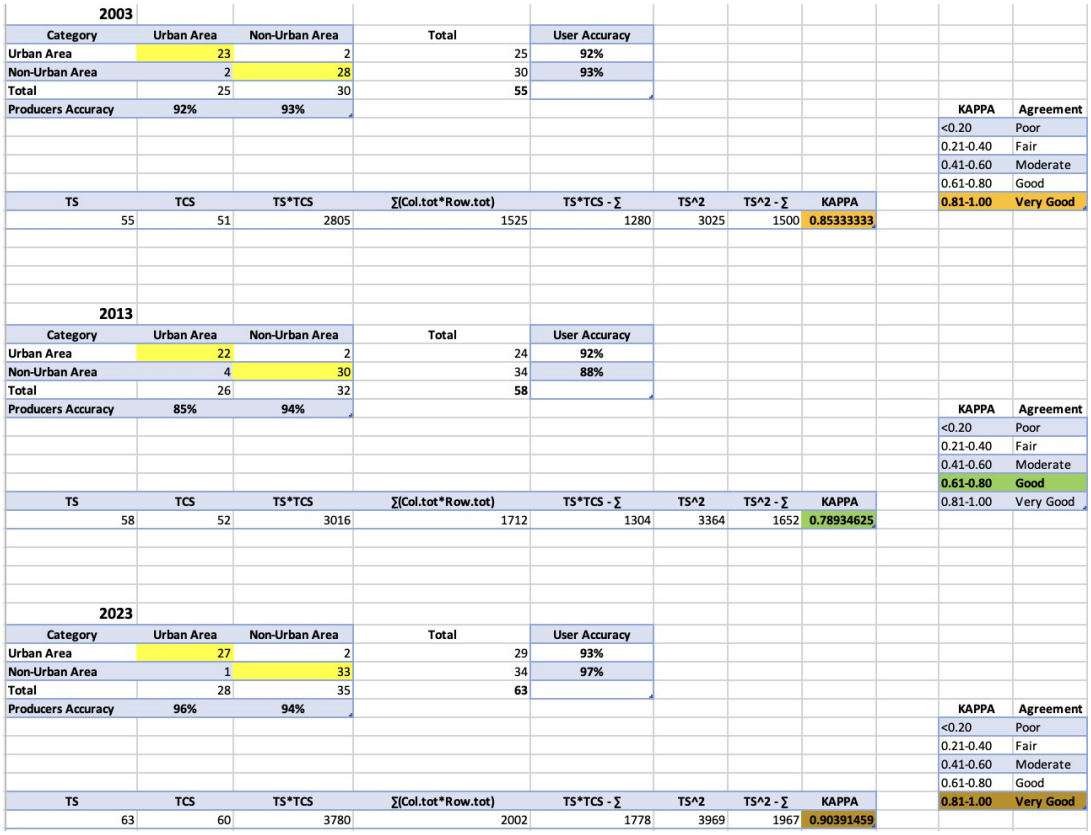
Figure 4: Combined GIS representation of Urban Expansion for 2003, 2013 and 2023

Source: Field Survey, 2023

The urban expansion map of Enugu Metropolis from 2003 to 2023 illustrates a significant and continuous transformation of land use over two decades (Figure 4). The maps reveal a progressive increase in urbanized areas, particularly in Enugu East, Enugu North, and Enugu South, indicating rapid urbanization driven by population growth and economic development. The spatial patterns show a consistent outward expansion from the city center, with urban areas encroaching into previously non-urban zones.

The spatiotemporal analyses of urban change in Enugu Metropolis, as depicted in Figures 1 to 4, reveal pronounced contraction of non-urban areas concomitant with the expansion of urban areas over the three distinct epochs of 2003, 2013, and 2023. The results show that between 2003 and 2013, the urban area underwent a significant transformation, with a notable 49.91% change in area, indicating a rapid pace of urbanization. In contrast, the subsequent decade (2013-2023) witnessed a deceleration in the rate of urban expansion, with a recorded change of 19.69%, suggesting a slowdown in the metropolis's urban growth trajectory.

Accordingly, a confusion matrix was conducted to validate the model accuracy, in consistency with Heydarian et al. (2022) who confirms its capacity to generate insights for model validation and refinement. The results of this analysis are presented in Figure 5.



2003

Category	Urban Area	Non-Urban Area	Total	User Accuracy
Urban Area	23	2	25	92%
Non-Urban Area	2	28	30	93%
Total	25	30	55	
Producers Accuracy	92%	93%		

TS	TCS	TS*TCS	∑(Col.tot*Row.tot)	TS*TCS - ∑	TS^2	TS^2 - ∑	KAPPA
55	51	2805	1525	1280	3025	1500	0.85333333

KAPPA	Agreement
<0.20	Poor
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Good
0.81-1.00	Very Good

2013

Category	Urban Area	Non-Urban Area	Total	User Accuracy
Urban Area	22	2	24	92%
Non-Urban Area	4	30	34	88%
Total	26	32	58	
Producers Accuracy	85%	94%		

TS	TCS	TS*TCS	∑(Col.tot*Row.tot)	TS*TCS - ∑	TS^2	TS^2 - ∑	KAPPA
58	52	3016	1712	1304	3364	1652	0.78934625

KAPPA	Agreement
<0.20	Poor
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Good
0.81-1.00	Very Good

2023

Category	Urban Area	Non-Urban Area	Total	User Accuracy
Urban Area	27	2	29	93%
Non-Urban Area	1	33	34	97%
Total	28	35	63	
Producers Accuracy	96%	94%		

TS	TCS	TS*TCS	∑(Col.tot*Row.tot)	TS*TCS - ∑	TS^2	TS^2 - ∑	KAPPA
63	60	3780	2002	1778	3969	1967	0.90391459

KAPPA	Agreement
<0.20	Poor
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Good
0.81-1.00	Very Good

Figure 5: Confusion Matrix

The classification accuracy for the three epochs (2003, 2013, and 2023) was evaluated using user accuracy and Kappa agreement metrics. The results indicate that in 2003, the overall accuracy was 92%, with a Kappa value of 0.8533, classified as "Very Good" agreement. In 2013, the overall accuracy slightly decreased to 90%, with a Kappa value of 0.7893, categorized as "Good" agreement, while in 2023, the overall accuracy improved to 95%, with a Kappa value of 0.9039, indicating "Very Good" agreement.

Temporal analysis involved a comparative evaluation of the accuracy metrics across the three epochs reveals an upward trend, suggesting an improvement in the accuracy of land use classification over time. The increasing accuracy enhances the reliability and validity of the primary data. The user accuracy for urban areas remains consistently high across the years, indicating reliable identification of urban land use. Non-urban areas also exhibit high accuracy, particularly in 2023.

The Kappa values consistently fall within the "Very Good" agreement category, suggesting a robust classification process and a reliable representation of land use changes in Enugu Metropolis. This validates the credibility of the land use classification results, providing confidence in using this data for studying land use changes in Enugu Metropolis. The findings have implications for urban planning and development strategies, as they provide a reliable foundation for decision-making. The accuracy and agreement values in the classification data support its utility for analyzing land use changes in Enugu Metropolis, thereby informing effective planning and development initiatives.

5. Predictive Modelling of Land Use Dynamics

This subsection delves into the spatial patterns that emerged from the data analysis, with a focus on exploring

potential urban growth predictions based on the observed trends. To achieve this, two quantitative measures were employed: the Urban Expansion Intensity Index and Shannon's Entropy. These metrics facilitated an enhanced understanding of the spatial dynamics driving urban growth in Enugu Metropolis.

The Urban Expansion Intensity Index (Figure 6) provided insights into the rate and pattern of urban expansion, while Shannon's Entropy shed light on the complexity and disorder of urban land use configurations. The essence is to distil valuable information for predicting future urban growth and development trends.

CLASS_NAME	YEAR	YEAR	YEAR
LAND CATEGORY	2003	2013	2023
	Sq.Km	Sq.Km	Sq.Km
URBAN AREA	76.0572	114.018	136.4733
NON-URBAN AREA	481.501	443.54	421.085
TOTAL AREA	557.5582	557.558	557.5583
TOTAL AREA AVERAGE	557.5581		557.55815
TIME PERIOD	10		10
UEII=|ULAib - ULAia/t|TLAi X 100			

YEAR	ULA_{ib}	ULA_{ia}	$ULA_{ib} - ULA_{ia}$	t	$ULA_{ib} - ULA_{ia}/t$	TLA_i	$\|ULA_{ib} - ULA_{ia}/t\|TLA_i$	UEII
2003-2013	114.018	76.0572	37.9608	10	3.79608	557.5581	0.006808403	0.68
2013-2023	136.4733	114.018	22.4553	10	2.24553	557.55815	0.004027436	0.40

UEII for 2003-2013	0.68	Medium-Speed
UEII for 2013-2023	0.4	Low-Speed

0 to 0.28	Slow
0.28 to 0.59	Low-Speed
0.59 to 1.05	Medium-Speed
1.05 to 1.92	High Speed
> 1.92	Very High Speed

Figure 6: Urban Expansion Intensity Index

The values of the temporal Analysis of Urban Expansion Intensity Index (UEII) reveal a notable decrease in urban expansion intensity in Enugu Metropolis over the study period. Specifically, the UEII value of 0.68 observed between 2003 and 2013 indicates a medium urban expansion speed, whereas the UEII value of 0.40 observed between 2013 and 2023 suggests a low urban expansion speed. This decline in UEII values implies a slowdown in the rate of urban expansion in the metropolis over the latter period.

Shannon's Entropy Analysis (Figures 7 to 10) presents the absolute entropy values for the study area at each data point (2003, 2013, and 2023). These values provide a quantitative measure of the complexity and disorder of urban land use configurations in Enugu Metropolis, allowing for an examination of the spatial patterns and trends in urban development over time.

2003

ABSOLUTE ENTROPY

	ZONE	TOTAL AREA (SQ.K	URBAN AREA	Pi	1/Pi	Ln(1/Pi)	Pi*Ln(1/Pi)
	1	12.56565	6.94387	0.552607306	1.80960329	0.593107645	0.327755618
2003	2	50.2641	29.3699	0.584311666	1.711415429	0.537320764	0.313962791
	3	113.0951	47.743	0.422149147	2.368831033	0.862396598	0.364059988
	4	201.0592	58.8802	0.292850066	3.414716662	1.228094521	0.359647562
	5	297.6578	64.6908	0.21733279	4.601238507	1.526325508	0.33172058
	6	363.0368	66.8348	0.184099243	5.431852867	1.692280304	0.311547523
	7	423.0659	68.6929	0.162369267	6.158800982	1.817882113	0.295168186
	8	477.1054	70.8484	0.148496328	6.734173249	1.907195048	0.283211462
	9	523.8671	74.0201	0.141295569	7.07736277	1.956901348	0.27650149
	10	550.982	75.599	0.137207749	7.288218098	1.986259085	0.272530138
	11	557.5582	76.0572	0.13641123	7.330774733	1.992081204	0.271742248
					ABSOLUTE	Σ	3.407847584

	Zone 01	Zone 02	Zone 03	Zone 04	Zone 05	Zone 06	Zone 07	Zone 08	Zone 09	Zone 10	Zone 11
Non-Urban	5.62178	20.8942	65.3521	142.179	232.967	296.202	354.373	406.257	449.847	475.383	481.501
Urban Area	6.94387	29.3699	47.743	58.8802	64.6908	66.8348	68.6929	70.8484	74.0201	75.599	76.0572
Total	12.56565	50.2641	113.0951	201.0592	297.6578	363.0368	423.0659	477.1054	523.8671	550.982	557.5582

Figure 7: Absolute Antropy (2003)

2013

	ZONE	TOTAL AREA	URBAN AREA	Pi	1/Pi	Ln(1/Pi)	Pi*Ln(1/Pi)
	1	12.56567	9.59169	0.763324996	1.310057977	0.270071394	0.206152245
2013	2	50.2641	38.2024	0.760033503	1.315731472	0.274392764	0.208547693
	3	113.0953	65.277	0.577185789	1.732544388	0.549591072	0.317216157
	4	201.0591	83.9691	0.41763392	2.394441527	0.873150021	0.364657066
	5	297.6574	95.0104	0.319193811	3.13289282	1.141956801	0.364505544
	6	363.0368	98.9538	0.272572367	3.668750467	1.299851132	0.3543035
	7	423.066	101.13	0.239040717	4.183387719	1.431121377	0.34209628
	8	477.105	104.353	0.218721246	4.572029554	1.51995721	0.332446935
	9	523.867	108.066	0.206285183	4.847657913	1.578495684	0.325620271
	10	550.983	112.762	0.204656042	4.88624714	1.586424553	0.32467137
	11	557.558	114.018	0.204495317	4.89008753	1.587210203	0.324577054
					ABSOLUTE	∑	3.464794115

	Zone 01	Zone 02	Zone 03	Zone 04	Zone 05	Zone 06	Zone 07	Zone 08	Zone 09	Zone 10	Zone 11
Non-Urban	2.97398	12.0617	47.8183	117.09	202.647	264.083	321.936	372.752	415.801	438.221	443.54
Urban Area	9.59169	38.2024	65.277	83.9691	95.0104	98.9538	101.13	104.353	108.066	112.762	114.018
Total	12.56567	50.2641	113.0953	201.0591	297.6574	363.0368	423.066	477.105	523.867	550.983	557.558

Figure 8: Absolute Antropy (2013)

2023

	ZONE	TOTAL AREA	URBAN AREA	Pi	1/Pi	Ln(1/Pi)	Pi*Ln(1/Pi)
	1	12.565647	9.521097	0.757708457	1.319768825	0.277456589	0.210231204
2023	2	50.26412	40.56935	0.807123451	1.238967841	0.214278647	0.172949321
	3	113.09545	74.18905	0.65598616	1.524422405	0.421615587	0.27657399
	4	201.0592	102.0852	0.507737025	1.969523496	0.677791633	0.344139907
	5	297.6583	118.2463	0.397255175	2.517273691	0.923176447	0.366736621
	6	363.0365	123.3485	0.339768866	2.943177258	1.079489698	0.366776991
	7	423.0653	125.2763	0.296115753	3.377057752	1.217004843	0.360374306
	8	477.1054	129.2904	0.270989178	3.690184267	1.305676394	0.353824172
	9	523.867	132.876	0.253644532	3.942525362	1.371821473	0.347955015
	10	550.9824	136.1134	0.247037655	4.047965887	1.398214505	0.345411632
	11	557.5583	136.4733	0.24476956	4.085475327	1.407438081	0.344498
					ABSOLUTE	∑	3.48947116

	Zone 01	Zone 02	Zone 03	Zone 04	Zone 05	Zone 06	Zone 07	Zone 08	Zone 09	Zone 10	Zone 11
Non-Urban	3.04455	9.69477	38.9064	98.974	179.412	239.688	297.789	347.815	390.991	414.869	421.085
Urban Area	9.521097	40.56935	74.18905	102.0852	118.2463	123.3485	125.2763	129.2904	132.876	136.1134	136.4733
Total	12.565647	50.26412	113.09545	201.0592	297.6583	363.0365	423.0653	477.1054	523.867	550.9824	557.5583

Figure 9: Absolute Antropy (2023)

Absolute vs Relative Log (2003-2023)

n = 11 (number of zones or buffer circles)			
	ABSOLUTE	RELATIVE	LOG (n)
2003	3.407847584		
2013	3.464794115		2.39789527279837 Ln (natural log of number of zones)
2023	3.48947116		
The change rate of urban 2013-2003			$H_{n2013} - H_{n2003}$
H_n is relative entropy at time t			0.023748548
			3%
The change rate of urban 2023-2013			$H_{n2023} - H_{n2013}$
			0.010291127
			1%

Figure 10: Absolute vs Relative log (2003-2023)

The Shannon's Entropy analysis revealed a consistent pattern of uncontrolled dispersion in urban expansion across the three epochs examined. The absolute entropy values for 2003, 2013, and 2023, which are 3.408, 3.465, and 3.489, respectively, all exceed the natural log of the number of zones (2.398) derived from the 11 buffer zones. This suggests that the urban expansion pattern in Enugu Metropolis throughout the study period was characterized by uncontrolled dispersion, indicative of a lack of planning and regulation in the development

process.

The findings confirm the prevalence of informal land markets, particularly at the fringes of the metropolis, where development is largely unplanned and unregulated. This phenomenon is often associated with the proliferation of informal settlements, inadequate infrastructure, and environmental degradation. The results of this analysis highlight the need for effective urban planning and management strategies to mitigate the negative consequences of uncontrolled urban expansion and promote more sustainable and equitable development in Enugu Metropolis.

In perspective, the Urban Expansion Intensity Index quantifies the rate and pattern of urban growth, showing a deceleration in expansion intensity over time. Shannon's Entropy further assesses the complexity and disorder in urban land use configurations, revealing a pattern of uncontrolled dispersion across the periods analyzed. This pattern suggests challenges in regulatory and planning frameworks, contributing to urban sprawl and informal land markets, particularly in metropolitan fringes.

6. Discussion of Results

The results of this study underscore the pronounced and complex dynamics of land use change within Enugu Metropolis over the past two decades. Analysis through GIS-based multi-temporal remote sensing data reveals a marked shift from non-urban to urban land uses, aligning with global urbanization trends and indicating significant urban expansion. Between 2003 and 2013, Enugu experienced a high rate of urbanization with a 49.91% increase in urban area, which slowed to 19.69% between 2013 and 2023. This deceleration may suggest a stabilization in the urban growth rate or potential impacts of regulatory and environmental constraints.

The UEII and Shannon's Entropy analyses provide further granularity to these findings. The UEII's observed decline, from a medium speed of urban expansion (0.68) in the first decade to a low speed (0.40) in the subsequent decade, implies a shift in growth patterns possibly due to saturation of high-demand urban zones and limited available land for expansion within city limits.

Shannon's Entropy values consistently exceeding the natural log threshold for the study zones indicate a pattern of uncontrolled dispersion, with urban growth expanding beyond regulated planning boundaries. This pattern corroborates the observed prevalence of informal land use practices, particularly on the metropolis's fringes, which are marked by sporadic, unplanned developments and limited infrastructure support. The entropy values, increasing from 3.408 in 2003 to 3.489 in 2023, further confirm the persistence of urban sprawl, highlighting both a lack of comprehensive regulatory enforcement and the appeal of peripheral zones for affordable settlement options.

Furthermore, the classification accuracy metrics support the reliability of these findings, as evidenced by the Kappa values for each epoch: a "Very Good" agreement of 0.8533 in 2003 and 0.9039 in 2023, with only a slight decline to 0.7893 in 2013. The overall improvement in classification accuracy from 2003 to 2023 enhances confidence in the precision of the spatial analysis, suggesting that more recent classifications can reliably inform planning and policy initiatives. Additionally, the high user accuracy for urban and non-urban classifications strengthens the dataset's validity, confirming the spatial consistency of urban land use transformations over time.

This study's insights into Enugu's evolving urban landscape hold implications for urban planners, policymakers, and environmental management professionals. The documented decline in urban expansion intensity, coupled with persistent spatial disorder, calls for targeted interventions to regulate urban growth and prevent further environmental degradation. Improved regulatory frameworks, stronger enforcement of planning laws, and the integration of sustainable land use practices are essential to mitigate the adverse effects of unplanned expansion and enhance urban resilience in Enugu.

7. Conclusion and Implications of the Study

This study presents a comprehensive analysis of land use dynamics in Enugu Metropolis over a two-decade period (2003–2023), employing Geographic Information Systems (GIS) and multi-temporal remote sensing data to systematically track and quantify shifts in urban and non-urban land use patterns. The findings reveal a pronounced expansion of urban land, predominantly at the expense of non-urban areas, including forested and grassland ecosystems. This trend underscores a sustained trajectory of urbanization, driven by interrelated factors such as population growth, economic activities, and rural-to-urban migration, which collectively exert pressure on land resources and alter the spatial structure of the metropolis.

The application of advanced analytical tools, including the Urban Expansion Intensity Index and Shannon's

Entropy, provides critical insights into the spatial and temporal dimensions of Enugu's urban growth. These metrics reveal a discernible decline in the intensity of urban expansion over time, coupled with a persistent pattern of uncontrolled and dispersed growth. Such findings highlight the challenges of managing rapid urbanization in a context where regulatory frameworks are either underdeveloped or inadequately enforced. This regulatory gap has led to fragmented urban development, characterized by the proliferation of informal settlements and the encroachment of urban areas into peri-urban and ecologically sensitive zones.

As a mid-sized urban center in a developing nation, Enugu exemplifies the broader challenges faced by cities in similar contexts, where urbanization often outpaces the capacity of planning institutions to manage growth effectively. The study underscores the urgent need for evidence-based urban policies that prioritize sustainable development, integrate environmental considerations, and address the socio-economic drivers of land use change. Furthermore, the findings advocate for the adoption of proactive planning measures, such as effective zoning regulations, greenbelt preservation, and infrastructure development, to curb unregulated urban sprawl and promote orderly growth.

The study also emphasizes the importance of leveraging advanced geospatial technologies, such as GIS and remote sensing, for continuous monitoring and assessment of land use dynamics. Regular updates to spatial datasets and the integration of real-time data into urban planning processes are essential for addressing the evolving challenges of urbanization in Enugu.

This study not only advances the understanding of urbanization processes in Enugu but also offers actionable recommendations for policymakers and urban planners. Implementing the proposed interventions, ranging from sustainable land use planning to enhanced regulatory enforcement, could pave the way for a more structured and equitable urban development trajectory. Such an approach would balance the demands of urban growth with the imperatives of environmental conservation and socio-economic sustainability. The following section broadens the implications of these findings, situating them within the wider discourse on urbanization in developing regions.

7.1 Theoretical Implications of the Study

This study advances the theoretical discourse on urban growth and land use dynamics by empirically applying multiple urban development theories comprising the Central Place Theory, Bid-Rent Theory, Urban Ecology Theory, and the Multiple Nuclei Model, within the context of a mid-sized city in a developing country. The findings demonstrate that Enugu's urban growth follows certain classical patterns, such as a central hub's appeal for economic activities (Central Place Theory) and the competition for proximity to the central business district (Bid-Rent Theory).

However, the complexity of urban sprawl, unregulated development, and multiple growth centers observed in Enugu suggests a deviation from traditional monocentric urban models, supporting the applicability of the Multiple Nuclei Model to cities experiencing fragmented, peripheral growth. This study thus enriches the understanding of urban theories by showcasing how socio-economic drivers and regulatory inadequacies affect land use transformations in contexts where urbanization often outpaces formal planning mechanisms.

Additionally, the consistent pattern of urban sprawl and entropy observed aligns with the Urban Sprawl Theory, emphasizing the need to reassess how urban dynamics theories apply in rapidly urbanizing areas with limited planning infrastructure. The study's integration of remote sensing and GIS with urban growth theories provides a robust analytical approach that can be adapted to similar studies across sub-Saharan Africa and other rapidly urbanizing regions, supporting broader theoretical frameworks for understanding land use dynamics under different socio-political and economic conditions.

7.2 Practical Implications

The practical insights from this study underscore the utility of GIS and remote sensing as indispensable tools for monitoring urban growth, offering spatial accuracy and temporal insights critical for effective urban management. Employing quantitative measures such as the Urban Expansion Intensity Index and Shannon's Entropy provides a replicable model for assessing urban sprawl and land use efficiency in Enugu and similar cities. Urban planners and environmental managers can leverage these tools to identify high-risk areas of unplanned development, facilitating targeted interventions and infrastructure planning.

The findings also highlight the importance of incorporating predictive modeling in urban planning practices to anticipate and address future growth pressures. With the observed trend of urban growth encroaching into peripheral areas, there is a clear practical need to establish buffer zones and enforce zoning regulations that prioritize sustainable land use. The research further suggests that integrating remote sensing data with urban

planning processes can enhance decision-making, enabling authorities to monitor land use changes in real time, allocate resources efficiently and mitigate risks associated with unplanned expansion. Practitioners in Enugu and similar urban centers can adopt this methodology to streamline their land use planning and ensure that urban growth aligns with environmental and socio-economic priorities.

7.3 Policy Implications

The study's findings carry significant policy implications for urban development and land management in Enugu and comparable urban areas across developing countries. The documented patterns of uncontrolled urban expansion and persistent spatial disorder reveal a critical need for policy reforms to strengthen urban governance and regulatory frameworks. Policies aimed at enforcing land use plans, improving land tenure security, and streamlining development approvals are essential to mitigate the growth of informal settlements and enhance regulatory compliance. Establishing a comprehensive urban policy framework that mandates the use of GIS and remote sensing data for monitoring urban growth can further strengthen land use management.

Furthermore, the observed deceleration in the rate of urban expansion from 2013 to 2023 suggests that well-enforced policies could support a controlled growth trajectory. Policymakers can draw on this insight to craft policies that balance urban development with environmental sustainability. Policies promoting infill development and densification in already urbanized areas can help optimize land use while preserving valuable peripheral ecosystems. Integrating socio-economic considerations into urban planning, such as affordable housing schemes, infrastructure investments, and accessible services, can reduce the need for fringe expansion and enhance the quality of urban life.

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