FOREST LOSS DYNAMICS AND TRANSFORMATIVE ADAPTATION: A SOCIO-ECOLOGICAL AND GEOSPATIAL ANALYSIS OF UDI FOREST, NIGERIA

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Abstract

This study examined the dynamics of forest loss in Udi Forest, Enugu State, Nigeria, by integrating geospatial analysis and socio-economic data, and assessed its implications for climate risk through the lens of transformative adaptation. While previous studies on deforestation in Nigeria have largely focused on land-cover dynamics or socio-economic drivers in isolation, limited attention has been paid to integrating long-term geospatial analysis with local-level perceptions to assess climate risk implications. To address this gap, a mixed-methods approach was adopted, combining geospatial techniques with socio-economic data. Primary data were obtained from 100 randomly administered questionnaires, key informant interviews, participant observation, and field photography. Land-use/land-cover (LULC) changes were analyzed using multi-temporal satellite imagery (2003–2023) at 30 m spatial resolution. Supervised classification yielded an overall accuracy of 87% and a Kappa coefficient of 0.83, indicating strong reliability. The results reveal significant landscape transformation over the two-decade period. Vegetation cover declined markedly from 65.00% in 2003 to 25.75% in 2023, while bare surfaces increased from 32.14% to 63.00%. Built-up areas expanded from 2.07% to 11.25%, reflecting intensified human activities and urban encroachment. Notably, water bodies, which constituted 0.50% of the study area in 2003, had completely disappeared by 2023. These patterns indicate rapid deforestation and ecosystem degradation driven primarily by unsustainable land-use practices. The environmental consequences include biodiversity loss, heightened soil erosion, ecosystem instability, and increased local temperature variability. By linking these changes to broader climate risks, the study highlights the need for transformative adaptation strategies that address structural drivers of deforestation. Such strategies should prioritize inclusivity, cross-scale governance, and long-term sustainability pathways to enhance ecological resilience and support climate adaptation in vulnerable forest landscapes.

Keywords: Deforestation, Forest loss, Geospatial Analysis, Land use Land cover, Transformative Adaptation.

INTRODUCTION

Climate change continues to intensify the degradation of ecological systems globally, with forest ecosystems among the most vulnerable. In Nigeria, forests are increasingly threatened by anthropogenic pressures and climate-induced stressors such as irregular rainfall, rising temperatures, and prolonged dry seasons (Food and Agriculture Organization, 2022). Forests are complex ecological systems dominated by tree cover and play critical roles in carbon sequestration, biodiversity conservation, soil stabilization, and livelihood support (FAO, 2020; Kimengsi *et al.,* 2023). Globally, they sustain over 1.6 billion people and harbor approximately 80% of terrestrial biodiversity (FAO, 2024).

To ensure conceptual clarity, this study adopts consistent operational definitions. *Forest loss* refers to the overall reduction in forest extent over time, encompassing both *deforestation* and *forest degradation.* Deforestation denotes the complete and permanent removal of forest cover for alternative land uses such as agriculture or urban development, while forest degradation describes the gradual decline in forest quality, structure, and ecological functioning without total canopy removal (FAO, 2020). Land use/land cover change (LULC) refers to the spatial transformation of land surfaces, including the conversion of vegetation into built-up areas, bare surfaces, or other categories. These concepts are applied consistently throughout this study.

Recent studies highlight the scale and dynamics of LULC change across Nigeria and sub-Saharan Africa. For instance, Ologunde *et al.* (2025) demonstrate that rapid conversion of vegetation to built-up and agricultural land significantly alters ecosystem stability and increases environmental risk. Similarly, Balogun *et al.* (2023) report a steady decline in vegetation cover alongside urban expansion in southwestern Nigeria, reflecting intensified anthropogenic pressure. At a broader scale, Akinyemi and Mashame (2023) show that LULC dynamics across sub-Saharan Africa are strongly linked to population growth and agricultural expansion, with significant implications for environmental sustainability.

In addition, global assessments emphasize that forest loss is largely driven by agricultural expansion, logging, and infrastructure development, with far-reaching impacts on climate systems and ecosystem services (Akanwa *et al*. 2022). Alkassim (2024) reported that Nigeria has lost 17,400Km2 in the last two decades from the year 2000 to 2020 to deforestation, including plants and animal species. The volume of the deforested area is the size of Lagos (3,577km2), Enugu (7,161km2) and the Federal Capital Territory (7,315km2) combined. Recent climate-focused studies further highlight that these land transformations exacerbate ecosystem vulnerability and undermine livelihoods, particularly in developing regions (Gbegbelegbe *et al.,* 2022; Owusu & Sarkodie, 2023).

Despite these advances, existing studies remain largely descriptive, focusing on mapping and quantifying land-cover transitions. A systematic review by Alegbeleye *et al*. (2024) notes that LULC research in Nigeria is predominantly method-driven, with limited integration of socio-economic drivers, local perceptions, and climate risk implications. In particular, most studies in southeastern Nigeria rarely link observed forest loss to adaptation processes or vulnerability dynamics, thereby limiting their policy relevance.

This reveals a critical research gap: the lack of integrated approaches that combine geospatial analysis of forest loss with socio-economic insights and climate risk frameworks. Furthermore, the application of transformative adaptation, emphasizing structural and systemic responses to environmental change, remains underexplored in forest landscape studies in Nigeria.

Udi Forest in Enugu State provides a compelling case for addressing this gap. Once characterized by dense vegetation and rich biodiversity, the area is increasingly experiencing forest loss driven by agricultural expansion, urban encroachment, and unsustainable land-use practices (IUCN, 2022). Deforestation levels in Enugu have intensified to such an extent that the Enugu State Government has warned against the illegal felling of trees (Agency Report, 2022). These pressures are exacerbated by weak institutional enforcement, population growth, and limited livelihood alternatives (Owusu & Sarkodie, 2023). The resulting land transformations have significant implications for ecosystem stability, local climate regulation, and community resilience.

In response, this study integrates remote sensing and GIS analysis with socio-economic data to examine forest loss and its climate risk implications in Udi Forest. By adopting a transformative adaptation framework, the study advances beyond conventional LULC assessments to explore pathways for sustainable and inclusive resilience.

Adaptation of the Transformative Approach

Transformative adaptation denotes profound and systematic alterations within social, ecological, and institutional frameworks to effectively tackle the challenges posed by climate change. In contrast to incremental adaptation, which emphasizes short–term modifications, transformative adaptation aspires to achieve enduring structural transformation in human-environment interactions to diminish vulnerability and bolster resilience (Pelling et al. 2015; Fazey *et al*. 2018). In forest ecosystems, particularly in Nigeria's Udi Forest in Enugu State, the significance of transformative adaptation is heightened by persistent deforestation, environmental degradation, and biodiversity loss driven by anthropogenic and climatic factors.

Udi Forest, historically a vital ecological region in southeastern Nigeria, has undergone significant degradation, driven by logging, agricultural expansion, and population growth. Scientifically observing these environmental transitions necessitates the integration of transformative methodologies with contemporary technologies, such as Geographic Information Systems (GIS) and Remote Sensing (RS). These technologies facilitate systematic evaluation of spatial and temporal changes in forest cover, assisting policymakers in formulating sustainable land-use and conservation strategies (Osemeobo, 2020; Zhu *et al*., 2019).

Crucially, the adoption of spatial technologies must be complemented by institutional reforms, environmental training, and decision-making that prioritizes long-term environmental integrity over short-term economic benefits.

The active participation of communities in monitoring and collaboratively managing forests constitutes a fundamental aspect of transformative adaptation. By equipping local stakeholders with technical resources and empowering local actors with technical tools and environmental expertise, the adaptation process can transition from a top-down approach to one that is participatory and sustainable (Few *et al*. 2017). In the context of Udi Forest, where livelihoods are intricately tied to land and natural resources, this principle holds particular significance.

Study Area

Udi Forest is located in the Udi Local Government Area of Enugu State, southeastern Nigeria, as seen in Figure 1. Udi lies between Latitudes 06° 19’0” N and 0°6 39’0” N and Longitudes 07° 10’ 0” E and 07° 26’ E. Udi is bounded by Affa in the North, Ebo in the East, Eziagu L.G.A. in the South, and the West (Figure 3). It lies within the tropical rainforest belt characterized by hilly terrain, lateritic soils, and distinct wet and dry seasons (Okonkwo & Igwe, 2018; NIMET, 2021). The area receives 1,500–2,000 mm of annual rainfall, supporting dense vegetation and agriculture. As part of the Enugu Escarpment, with elevations of 200–450 m, it serves as a vital water catchment and erosion control zone.

The population of Udi increased from 28,836 in 2006 (NPC, 2006) to an estimated 49,823 in 2024 using a 3.2% annual growth rate (World Bank, 2023), reflecting rising pressure on land and ecological resources. Rapid population growth is closely linked to deforestation, agricultural expansion, and forest exploitation, intensifying environmental degradation and climate risks (FAO, 2024).

Udi Forest has long provided timber, fuelwood, and non-timber products that sustain local livelihoods (Nwachukwu, 2019). However, increasing anthropogenic activities such as farming, settlement expansion, and logging have degraded forest cover, leading to soil erosion, declining fertility, reduced crop yields, and flooding (Chukwuemeka et al., 2020). In this agro-based region, dependence on subsistence farming heightens pressure on land, while weak policy enforcement accelerates forest fragmentation (Ugwunayi & Okafor, 2022). These dynamics threaten environmental sustainability and underscore the urgency for effective land-use planning and climate-resilient strategies.

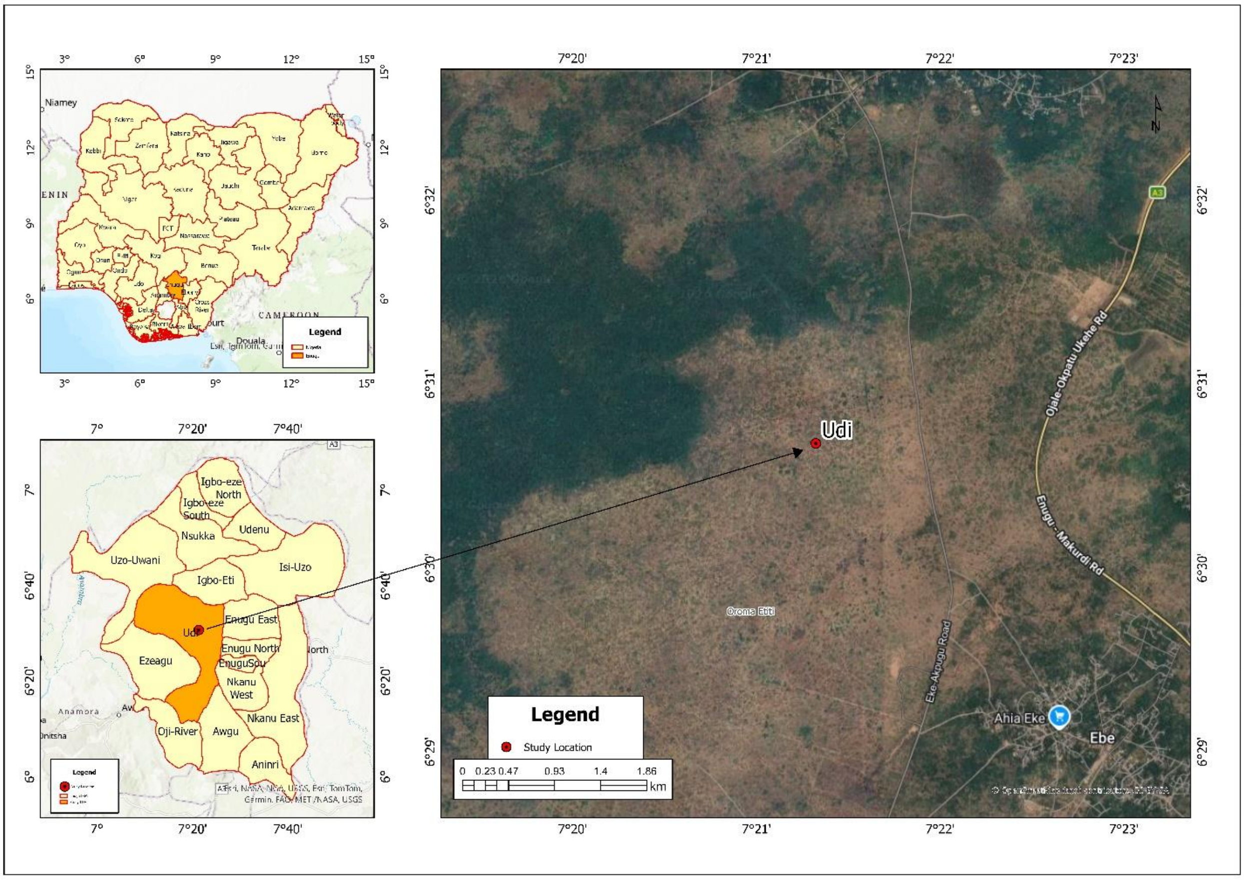

Figure 1: Map of the Udi Local Government Area showing Udi
Source: Compiled by authors (2026)

MATERIALS AND METHODS

This research utilized a mixed-methods approach, integrating both quantitative and qualitative methodologies alongside spatial analysis to investigate forest loss and its ramifications for climate-related risks in Udi Forest, located in Enugu State, Nigeria. This inquiry amalgamates primary data acquisition via surveys and interviews with geospatial analysis employing satellite imagery of 2003 and 2023 to delineate land use and land cover (LULC) alterations over twenty years. The secondary sources of data include documentary review and analysis from internet sources and published works.

Quantitative Data

The projected population of Udi (49,823) was estimated using a 3.2% annual growth rate from the 2006 census (NPC, 2006). The sample size of 100 respondents was determined using the Yamane (1967) formula at a 10% margin of error (e = 0.10), which is acceptable for exploratory studies under field constraints.

To ensure representativeness, a stratified sampling technique was employed. The study area was divided into forest-adjacent and non-forest communities, reflecting varying exposure to forest dynamics. Within each stratum, systematic random sampling was used to select respondents. This approach ensured inclusion of diverse socio-ecological perspectives.

The questionnaire captured demographic characteristics, land-use practices, perceptions of forest change, climate impacts, and adaptation strategies. Data collection was conducted through face-to-face administration by trained facilitators to enhance response accuracy and completeness.

Qualitative Data Collection

Qualitative data were obtained through Key Informant Interviews (KII) with eight purposively selected stakeholders, including forestry officials, community leaders, and an environmental NGO representative. These interviews provided insights into institutional frameworks, policy implementation, and historical forest use.

Participant observation and photographic documentation (Rose, 2016) was conducted to validate land-use practices such as logging and farming within and around the forest. Observations were supported with field notes and photographic documentation. Interviews conducted in Igbo were translated into English to preserve contextual meaning.

GIS and Remote Sensing Analysis

Land-use/land-cover (LULC) changes were analyzed using Landsat 7 ETM+ (2003) and Landsat 8 OLI (2023) imagery acquired from the USGS Earth Explorer. Both datasets have a spatial resolution of 30 m, suitable for regional-scale environmental monitoring.

Preprocessing steps included radiometric, atmospheric, and geometric corrections to ensure consistency across datasets. False-color composites were generated to enhance feature discrimination. Image processing and analysis were conducted using ArcGIS 10.8.

A supervised classification approach based on the Maximum Likelihood Classification (MLC) algorithm was employed due to its statistical robustness and effectiveness in handling spectral variability in heterogeneous landscapes. The classification scheme comprised four classes: vegetation, bare surface, built-up area, and water bodies. These classes were selected to capture dominant land-cover types and key environmental transitions relevant to deforestation and climate risk.

Accuracy Assessment and Change Detection

Training samples were developed using field knowledge and high-resolution reference imagery to ensure class separability. Classification accuracy was evaluated using independent validation points and a confusion matrix. The results yielded an overall accuracy of 87% and a Kappa coefficient of 0.83, indicating strong agreement and high classification reliability.

Post-classification comparison was employed as the change detection technique. This method involves independent classification of multi-temporal images followed by pixel-by-pixel comparison to quantify transitions between classes. It was selected for its robustness in minimizing sensor-related inconsistencies and enhancing temporal comparability.

The “bare surface” class included exposed soils, degraded lands, and fallow areas. Due to spectral similarities, some transitional agricultural lands were also captured within this class, particularly during dry seasons.

Data Analysis

Quantitative data were analyzed using SPSS version 26, employing descriptive statistics such as frequencies and percentages. Qualitative data were analyzed using thematic content analysis, while photographic evidence supported the interpretation of observed land-use practices. GIS outputs were presented through maps and statistical summaries to enhance spatial understanding of land-cover dynamics and climate risk patterns.

RESULTS AND DISCUSSION

This study integrates 100 administered questionnaire data, field observations, photographic evidence, and GIS-based land use/land cover (LULC) analysis to examine forest loss and its socio-environmental implications in Udi Forest, Enugu State. The triangulation of these datasets provides a more robust understanding of how livelihood systems, governance gaps, and land-use transitions interact to drive environmental change.

The socio-demographic characteristics of participants are revealed in Table 1. The findings include a predominantly male sample (62%), an economically active age group of 41–50 years (40%), and those aged 50 and above (31%). This suggests a mature and experienced population. A significant majority are married (78%), with most households having 4–8 children (68%), indicating relatively large family sizes and potential dependency pressures. Educational attainment is moderate, with over half holding SSCE/WAEC qualifications (52%), while fewer have a tertiary education. Farming dominates as the primary occupation (44%), reflecting a largely agrarian livelihood structure. Income levels are modest, with most earning ₦51,000–₦100,000 monthly (58%). Notably, reliance on fuelwood (58%) highlights persistent dependence on traditional energy sources, with implications for environmental sustainability and household health.

Table 1: Socio-Demographic Characteristics of Participants (N = 100)

No	Variable	Category	n (%)
1	**Gender**	Male	62 (62.0)
		Female	38 (38.0)
2	**Age (years)**	18–30	8 (8.0)
		31–40	21 (21.0)
		41–50	40 (40.0)
		≥50	31 (31.0)
3	**Marital Status**	Single	8 (8.0)
		Married	78 (78.0)
		Widowed	14 (14.0)
4	**Number of Children**	1–3	15 (15.0)
		4–8	68 (68.0)
		9–12	9 (9.0)
		Not applicable	8 (8.0)
5	**Education**	SSCE/WAEC	52 (52.0)
		NCE/OND	30 (30.0)
		BSc/HND	18 (18.0)
6	**Occupation**	Business	23 (23.0)
		Civil servant	8 (8.0)

		Student	5 (5.0)
		Driver	5 (5.0)
		Artisan	15 (15.0)
		Farmer	44 (44.0)
7	**Monthly Income (₦)**	31,000–50,000	23 (23.0)
		51,000–100,000	58 (58.0)
		100,000–150,000	19 (19.0)
8	**Cooking Energy Source**	Fuelwood	58 (58.0)
		Kerosene	18 (18.0)
		Gas cooker	24 (24.0)

Source: Compiled by authors (2026).

Table 2 captures the causes of deforestation, based on the summation of the ‘’agree and strongly agree options’’ (92%). Timber lumbering is the highest, followed by farming 46% and fuel wood, 60%. This could be a result of unregulated deforestation policies (72%), as indicated by the participants. The fuelwood finding (60%) validates the energy use pattern documented in Table 1, where 58% of households rely on fuelwood for cooking. Notably, 72% of the participants attributed these deforestation activities to weak policy enforcement and inadequate regulatory frameworks, suggesting that governance failures enable unsustainable forest exploitation.

Table 2: Causes of Deforestation in Udi Forest.

Variables	Strongly disagree	Disagree	Fair	Agree	Strongly agree	Frequency
Farming	-	29	25	46	-	100
Fuelwood	-	26	14	38	22	100
Timber Lumbering	-	-	8	29	63	100
Settlement	-	45	21	34	-	100
Sand mining	53	37	6	4	-	100
Palm oil processing	100	-	-	-	-	100
Poverty	-	46	22	32	-	100
Unregulated deforestation policies		7	21	25	47	100

Source: Compiled by authors (2026)

Table 3 reveals the distribution of uses for harvested resources from Udi Forest among 100 respondents. The findings show that 37% of respondents indicated "Not applicable," suggesting that the question did not apply to their circumstances. Among those who do utilize forest resources, construction purposes were the most common use (27%), followed by commercial purposes (16%) and fuel wood (15%). Agricultural purposes accounted for the smallest proportion at 5% of resource utilization. These findings suggest that while a significant portion of the population may not directly depend on Udi Forest resources, those who do utilize the forest demonstrate diversified resource extraction patterns, with construction materials being the dominant demand. The combined pressures indicate substantial resource extraction that could threaten forest sustainability if not properly managed through transformative adaptation or solutions.

Table 3: Uses of Harvested Resources from Udi Forest

Value	Frequency	Percent	Valid Percent	Cumulative Percent
Agricultural purposes	5	5.0	5.0	5.0
Construction purposes	27	27.0	27.0	32.0
Fuel wood	15	15.0	15.0	47.0
Commercial purposes	16	16.0	16.0	63.0
Not applicable	37	37.0	37.0	100.0
Total	100	100.0	100.0	

Source: Compiled by authors (2026)

Table 4 provides the dependency rate of forest resources on the community. 8% of the respondents opined a 25-50 ratio, 39% agreed that the dependency rate is 50-75, and 53% asserted 75-100. The community's dependency on the forest is high. These results highlight the critical role of Udi Forest in sustaining local livelihoods and highlight the community's vulnerability to forest degradation. The strong reliance necessitates urgent implementation of transformative measures involving sustainable forest management strategies and community-based conservation programs that ensure continued access to forest resources while preventing overexploitation.

Table 4: Dependency of the forest resources on the community

Ratio	Frequency	Percent	Valid Percent	Cumulative Percent
25- 50	8	8.0	8.0	8.0
50- 75	39	39.0	39.0	47.0
75-100	53	53.0	53.0	100.0
Total	100	100.0	100.0	

Source: Compiled by authors (2026)

Table 5 reveals the different environmental problems caused by deforestation: 63% indicated loss of biodiversity, 14% increased temperature, 20% flooding, and 3% loss of soil nutrients. This implies that the high dependency rate of forest resources on the community has caused environmental problems. The findings demonstrate strong community awareness of deforestation's multifaceted environmental impacts and suggest that conservation efforts should prioritize biodiversity protection while simultaneously addressing climate regulation and watershed management. The relatively low perception of soil nutrient loss may indicate either limited agricultural engagement with forest soils or insufficient awareness of this ecological consequence, highlighting a potential need for enhanced environmental education to foster a comprehensive understanding of deforestation's long-term effects on ecosystem services and agricultural productivity.

Table 5: Environmental problems caused by deforestation

Value	Frequency	Percent	Valid Percent	Cumulative Percent
Loss of biodiversity	63	63.0	63.0	63.0
Increased temperature	14	14.0	14.0	77.0
Flooding	20	20.0	20.0	97.0
Loss of soil nutrients	3	3.0	3.0	100.0
Total	100	100.0	100.0	

Source: Compiled by authors (2026)

RESULTS AND DISCUSSION

Socio-economic Structure and Livelihood Dependence

The socio-demographic profile of the participants reveals a predominantly economically active and agrarian population. The dominance of farming and moderate income levels concentrated between ₦51,000–₦100,000 falls within the Nigerian minimum wage (Vanguard News, 2024), reflecting its agrarian structure. This reinforces the link between income generation and environmental pressure (World Bank, 2023).

The livelihood structure reflects a high dependence on natural resources, particularly in contexts where alternative income opportunities remain limited. This aligns with national evidence that agriculture remains the primary rural livelihood in Nigeria (National Bureau of Statistics, 2022).

This reliance on farming indicates strong human–environment interactions, where land clearing for agriculture and fuelwood collection drives deforestation. Similar patterns have been observed across rural Nigeria, where livelihood dependence on forests contributes to ecosystem degradation (FAO, 2022). The gender distribution reflects male dominance in land-based activities such as logging and farming, consistent with gendered resource control systems in southeastern Nigeria (UNDP, 2021).

The age distribution indicates that 71% of participants are above 40 years, indicating that older adults are more actively involved in land use and forest-related activities due to land ownership and experience. This pattern aligns with findings by Balogun *et al.* (2023), who observed that rural land management in southwestern Nigeria is concentrated among older households due to inheritance-based land tenure systems. Similarly, Akinyemi and Mashame (2023) noted that such demographic structures reinforce extractive land-use practices in sub-Saharan Africa. However, younger individuals (18–30 years) represent only 8%, who are less engaged, often due to rural–urban migration and limited access to land (Akinyemi & Olaniyi, 2021).

Fuelwood dependence (58%) further reflects persistent energy poverty. This finding is consistent with Owusu and Sarkodie (2023), who argue that reliance on biomass energy in developing regions is both a cause and consequence of forest degradation. Importantly, the alignment between household energy use and reported deforestation drivers indicates that environmental pressure is structurally embedded in daily survival systems rather than isolated illegal activities.

Drivers of Deforestation and Forest Degradation

Household structure indicates that 78% of participants are married, with 68% having 4–8 children, exceeding national averages (NBS, 2022). Larger households increase demand for land, fuelwood, and construction materials, intensifying forest degradation (Taylor, 2024). Additionally, 63% of participants reported active participation in tree felling, confirming that deforestation is embedded in livelihood systems. Energy use patterns showed that 58% depend on fuelwood, compared to 18% using kerosene and 24% gas, reflecting widespread reliance on biomass energy in rural Africa (IEA, 2022). This dependence contributes significantly to deforestation and carbon emissions.

While participants identified timber extraction, fuelwood collection, and agriculture remain the leading drivers of forest loss as shown in Plates 1 and 2, highlighting intense anthropogenic pressure. The prominence of timber extraction (92%) reflects the commercialisation of forest resources, a pattern similarly reported by Ologunde et al. (2025), who found that market-driven logging intensifies land-cover conversion in Nigeria. However, the underlying issue is not only extraction intensity but also institutional failure, as 72% of participants attributed forest loss to weak enforcement mechanisms. Weak governance structures have been widely linked to unsustainable forest exploitation in developing countries (Kimengsi *et al.*, 2023). The unanimous perception (100%) of increasing deforestation confirms visible environmental decline. This aligns with Alegbeleye et al. (2024), who emphasize that governance gaps remain the weakest dimension in Nigeria's forest management systems. Thus, deforestation in Udi Forest is better interpreted as a governance-livelihood nexus rather than a purely economic or environmental phenomenon.

Plate 1: Deforestation, logging, and harvest of trees for fuel wood and agricultural activities at Udi Forest.

Plate 2: Harvested trees for fuel wood and wood from Udi Forest being transported to other areas

Forest Resource Use and Pressure Intensification

Findings on forest resource utilization show that construction materials dominate extraction patterns, followed by commercial and fuelwood uses. This suggests a shift from subsistence-only dependence to mixed subsistence-commercial exploitation.

This trend mirrors broader regional patterns documented by Kimengsi *et al*. (2023), who argue that forest dependence in the Global South is increasingly shaped by market integration and rural commodification of natural resources. The relatively high proportion of participants indicating “not applicable” (37%) does not necessarily imply low dependence; rather, it may reflect indirect dependence through household networks and value chains.

Environmental Perception and Risk Awareness

Participants indicated strong awareness of biodiversity loss and flooding, indicating that environmental degradation is both visible and locally experienced. However, the relatively low recognition of soil nutrient depletion (3%) suggests uneven ecological awareness and remains critical due to erosion and declining agricultural productivity (Lal, 2020; Akanwa *et al*., 2024).

This pattern is consistent with Owusu and Sarkodie (2023), who note that communities often prioritize immediate and visible environmental changes (flooding, heat stress) over gradual soil degradation processes. The implication is that environmental perception is influenced more by direct experience than scientific understanding.

These environmental impacts weaken ecosystem services such as soil fertility, water regulation, and climate stability. Flooding is linked to reduced canopy cover and infiltration, increasing surface runoff (Ojoatre *et al*. 2023), while 14% reported rising temperatures due to altered microclimates from forest loss.

Key informant interviews reveal that deforestation is driven by poverty, unemployment, and reliance on fuelwood. This reinforces the "livelihood–forest nexus" as noted by Ajayi *et al.* (2020). Integrating indigenous knowledge with environmental education can foster behavioural change (Chazdon *et al.*, 2020). Though the educational attainment of the participants is relatively high, with 52% holding SSCE/WAEC and 30% NCE/OND qualifications. This indicates that education should enhance environmental awareness and support the adoption of sustainable practices (UNESCO, 2021). However, economic necessity often overrides environmental considerations, reflecting strong dependence on forest resources in spite of high educational levels (FAO &UNITAR, 2025).

Participants emphasized economic alternatives, with calls for skills and financial support to reduce forest pressure (Mbow *et al.*, 2019). Obviously, unregulated logging, agricultural expansion, and limited livelihoods drive unsustainable practices, highlighting the need for transformative and integrated interventions.

These findings demonstrate that deforestation in Udi Forest is driven by interconnected socio-economic factors, including population growth, energy poverty, weak governance, and livelihood dependence. Addressing these challenges requires integrated strategies that combine sustainable land use, alternative livelihoods, clean energy access, and strengthened institutional frameworks.

Land Use/ Land Cover Change (LULC) from 2003 to 2023 at Udi Forest Area

The land use and land cover (LULC) classification for 2003 is presented in Figure 2 and Table 6, which provides a critical ecological baseline before intensified anthropogenic pressure. In 2003, vegetation dominated the landscape, covering 2,051.6 hectares (65.30%) of the total 3,141.8 hectares, indicating a relatively intact ecosystem with strong capacity for biodiversity support and climate regulation (FAO, 2022; IPCC, 2021). Bare surfaces accounted for 32.14% (1,009.7 ha), suggesting early land disturbance linked to subsistence agriculture and initial deforestation processes. Such transitional landscapes are characteristic of regions undergoing gradual land-use conversion driven by rural livelihoods.

Table 6: LULC analysis for 2003

Type	Area	Percentage
Bare Surface	1009.7	32.14
Built-up Area	65.0	2.07
Vegetation	2051.6	65.30
Waterbody	15.6	0.50
Total	3141.8	100.00

Source: Compiled by authors (2026)

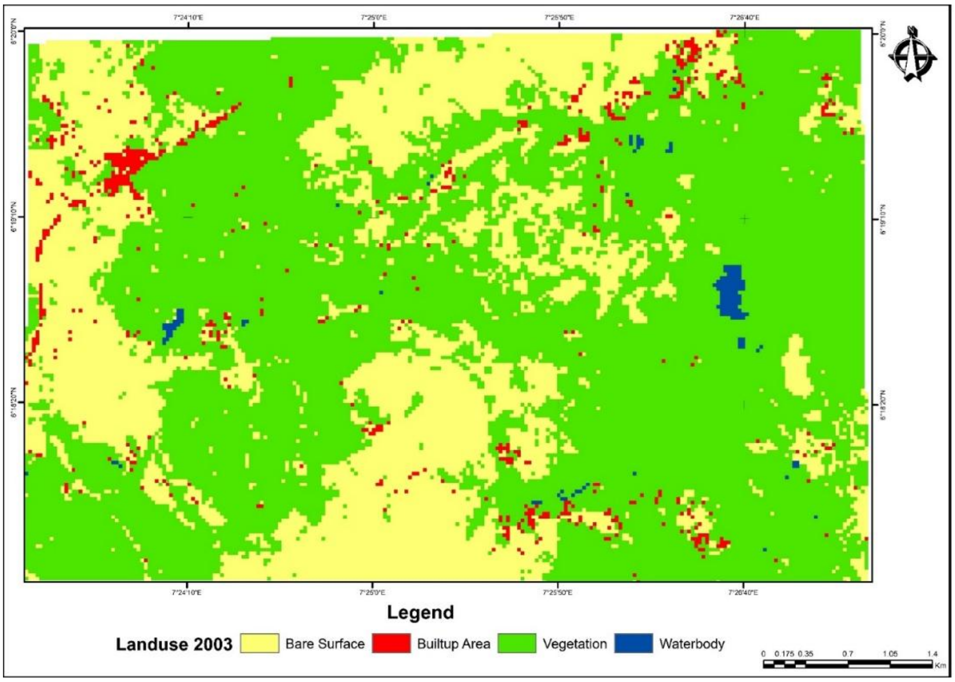

Figure 2: LULC of Udi Forest Area for 2003
Source: Compiled by authors (2026)

Figure 3, Table 7, and 8 indicate that by 2023, the landscape had undergone substantial transformation. Bare surfaces expanded dramatically to 63.00% (1,979.4 ha), indicating extensive deforestation, land degradation, and unsustainable agricultural expansion (Ikedigwe et al., 2024). In this study, bare surface includes exposed soils, degraded lands, fallow lands, and sparsely vegetated areas. This also covers farmlands, lawns, and transitional vegetation, especially during non-growing or dry seasons, which were classified under this category due to their spectral similarities in satellite imagery.

Vegetation declined sharply to 25.75% (809.1 ha), confirming severe forest loss and associated ecological consequences, including biodiversity decline and increased climate vulnerability (Global Forest Watch, 2024). Built-up areas increased to 11.25% (353.3 ha), reflecting rapid urbanization and demographic pressure, consistent with broader land-use change patterns in sub-Saharan Africa (UN-Habitat, 2022).

Table 7: LULC analysis for 2023

Type	Area	Percentage
Bare Surface	1979.4	63.00
Built-up Area	353.3	11.25
Vegetation	809.1	25.75
Total	3141.8	100.00

Source: Compiled by authors (2026)

A critical finding is the complete disappearance of water bodies, declining from 0.50% (15.6 ha) in 2003 to 0% in 2023. This indicates significant disruption of local hydrological systems, with implications for water availability, ecosystem services, and human well-being (UNEP, 2021). These spatial changes, validated through GIS analysis and field observations (Figure 3), highlight a clear shift from a predominantly vegetated system to a degraded, human-dominated landscape.

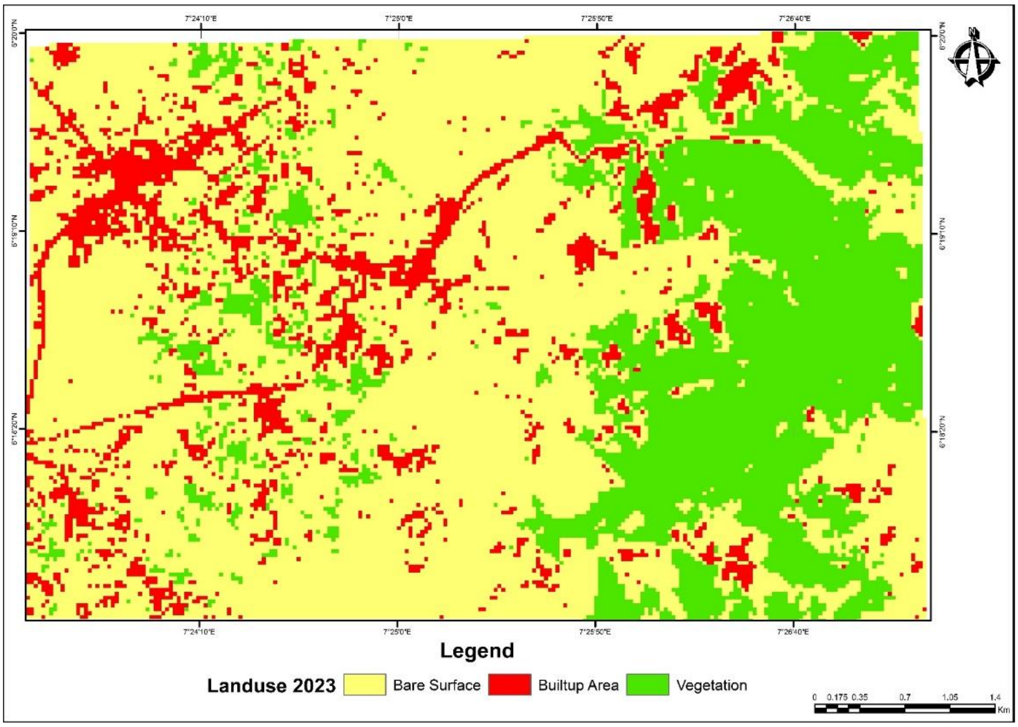

Figure 3: LULC Analysis of Udi Forest Area in 2023

Table 8: LULC change detection in the Udi Forest Area

Type	2003		2023		Percentage Change (%)
	Area	Percentage	Area	Percentage	
Bare Surface	1009.7	32.14	1979.4	63.00	+30.9
Built-up Area	65.0	2.07	353.3	11.25	+9.2
Vegetation	2051.6	65.30	809.1	25.75	-39.5
Waterbody	15.6	0.50	0.0	0.00	-0.5
Total	3141.8	100.00	3141.8	100.00	0.0

Source: Compiled by authors (2026)

In summary, the results demonstrate that population growth, agricultural expansion, and weak land governance have accelerated forest degradation in Udi. The strong agreement between spatial data and community perceptions indicates the urgency for integrated interventions, including reforestation, sustainable land-use planning, and strengthened institutional frameworks. Without such measures, continued environmental decline will further threaten biodiversity, ecosystem services, and climate resilience in the region (IPCC, 2021; FAO, 2022).

Integrated Interpretation of Change Drivers

The convergence of socio-economic and spatial data indicates that forest loss in Udi is not driven by a single factor but by interacting pressures: livelihood dependence, weak governance, population growth, and urban expansion.

Unlike earlier studies that treat LULC as a mapping exercise (Alegbeleye et al., 2024), this study demonstrates that spatial change is inseparable from social structure. The alignment between survey responses and GIS outputs strengthens the validity of the findings and confirms that community perceptions reflect observable environmental transformation.

Implications for Sustainability and Climate Risks

The findings extend beyond descriptive outcomes to reveal critical sustainability and climate risk implications for Udi Forest as a coupled human–environment system. First, structural dependence on forest resources persists despite clear environmental decline, indicating that degradation does not inherently reduce resource use. Instead, livelihood insecurity, energy poverty, and limited economic alternatives reinforce continued extraction, even as ecosystem conditions deteriorate. This not only affects sustainability but also intensifies climate risks, as continued deforestation reduces carbon sequestration capacity, increases greenhouse gas emissions, and heightens local temperature variability. Consequently, communities become more exposed to heat stress and declining environmental quality.

Second, governance deficiencies function as amplifiers rather than primary drivers of deforestation. While forest exploitation is rooted in livelihood needs, weak institutional enforcement enables its scale and persistence. This dynamic exacerbates climate vulnerability by allowing unchecked land conversion, which disrupts ecological regulation processes such as rainfall patterns and watershed stability. Thus, regulatory measures alone are insufficient; effective responses must integrate institutional strengthening with livelihood restructuring and inclusive governance systems to reduce both environmental degradation and associated climate risks.

Third, the evidence points to emerging ecological threshold conditions, reflected in the sharp decline in vegetation cover and the disappearance of water bodies. These changes signal not only environmental degradation but also heightened climate risk, including increased flooding due to reduced infiltration, prolonged dry conditions linked to loss of moisture regulation, and declining water availability. Once such thresholds are crossed, ecosystem recovery becomes more difficult, and communities face compounded risks from both environmental and climate stressors.

These insights reposition Udi Forest as a transitioning socio-ecological system, shifting from a relatively resilient ecological base to a degraded, climate-vulnerable landscape. This transition highlights the urgency for restoration-oriented and system-based interventions that simultaneously address ecological recovery, livelihood transformation, and governance reform. Without such integrated approaches, both sustainability and climate resilience in the region will remain severely constrained.

The Need for Transformative Adaptation in Udi Forest

The rapid degradation of Udi Forest shows that conventional conservation measures are no longer adequate to address ongoing forest loss. The observed decline in vegetation, expansion of bare land, and rising dependence on forest resources reflect a system under sustained ecological pressure. This calls for transformative adaptation, defined as a fundamental restructuring of the social, economic, and institutional drivers of environmental change.

At the centre of this shift is the recognition that forest loss is both a livelihood and governance problem. Communities depend heavily on the forest for fuelwood, farming inputs, and income, while enforcement of forest regulations remains weak. Policy responses must therefore address the root causes of deforestation, particularly poverty, energy insecurity, and limited livelihood options.

A key intervention is livelihood diversification through skill development, small enterprise support, and agroforestry systems that reduce dependence on forest extraction (Ajayi et al., 2020). Closely linked is the need for an energy transition strategy that expands access to clean cooking technologies such as LPG, improved cookstoves, and renewable energy alternatives to reduce fuelwood demand.

Institutional strengthening is also essential. Weak enforcement structures require improved funding, monitoring capacity, and community-based co-management systems that enhance accountability and compliance (Sovacool et al., 2021). In parallel, ecological restoration through assisted natural regeneration and reforestation with native species is critical for recovering degraded landscapes and restoring ecosystem services (Chazdon et al., 2020).

Community participation and indigenous knowledge must underpin all interventions, as local perceptions align strongly with observed environmental change (Mbow et al., 2019). Finally, cross-sectoral coordination across forestry, agriculture, energy, and land-use planning is necessary to ensure policy coherence. Hence, transformative adaptation offers a pathway to restore ecological integrity while securing sustainable rural livelihoods in Udi Forest.

CONCLUSION

This study integrated survey data from 100 respondents, qualitative field observations, and GIS-based land use/land cover (LULC) analysis covering 2003–2023 to examine forest loss in Udi Forest, Enugu State. Guided by a socio-ecological systems and transformative adaptation framework, the study conceptualised forest change as the outcome of interactions between livelihood dependence, institutional capacity, and land-use transitions. The findings show a pronounced shift from a vegetation-dominated landscape in 2003 to a highly degraded system in 2023, marked by significant vegetation loss, expansion of bare surfaces, and increasing built-up areas. These changes indicate progressive ecosystem fragmentation and reduced ecological integrity.

The results demonstrate that deforestation is largely driven by socio-economic dependence on forest resources, particularly agriculture, fuelwood consumption, and timber extraction. These pressures are reinforced by household income constraints, limited access to alternative energy sources, and weak forest governance structures. The disappearance of water bodies further reflects deeper hydrological disruption and declining ecosystem functionality, suggesting that the system is approaching critical ecological thresholds.

The strong convergence between GIS outputs and community perceptions validates the integrated methodological approach and confirms that local experiences mirror spatially observed environmental change. This reinforces the value of combining remote sensing with socio-economic data to understand complex land-use dynamics.

The study concludes that continued reliance on forest-based livelihoods, combined with weak institutional enforcement and increasing land-use pressure, will intensify ecosystem degradation and undermine long-term environmental resilience. These trends have significant implications for biodiversity conservation, climate regulation, and rural sustainability.

Addressing these challenges requires transformative adaptation through livelihood diversification, clean energy access, strengthened governance, and ecological restoration. Effective implementation depends on participatory approaches that ensure community ownership and cross-sector collaboration for sustainable forest management.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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