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Modelling Changes in Land Use Land Cover in the Sudan Savannah Ecological Zone of Northwestern Nigeria

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ABSTRACT

Climate change is one of the most global environmental concerns in the 21st century. This study modelled the historical changes and future projections of Land Use Land Cover (LULC) in the Sudan Savanna ecological zone of Northwestern Nigeria. The research analyzed multi-temporal Landsat imagery (2004, 2014, and 2024) to quantify past trends and projected future scenarios for 2035, 2045, and 2055. A supervised classification approach was employed to generate LULC maps, while CA-Markov modelling integrated with MOLUSCE plugin in QGIS was used for future projections. Model performance was rigorously validated using Neural Network learning curves and Pontius' multiple-resolution budget analysis. Results revealed a consistent increase in bare surface from 50.7% in 2004 to 53.36% in 2024, with a corresponding decline in vegetation cover from 48.56% to 45.77%. Projections indicate continued and accelerated vegetation loss, with bare surface becoming overwhelmingly dominant by 2055, especially in the central and eastern part of the study area. This study provides credible, spatially explicit evidence of ongoing land degradation and anthropogenic activities in the Sudan Savanna zone. The findings underscore the urgent need for sustainable land management, reforestation, and climate adaptation strategies to mitigate projected environmental risks and enhance resilience in Northwestern Nigeria.

Keywords: Land Use Land Cover, CA-Markov, Sudan Savanna, Northwestern Nigeria, Climate Change

RÉSUMÉ

Le changement climatique est l'une des préoccupations environnementales majeures du XXIe siècle. Cette étude a modélisé l'évolution historique et les projections futures de l'occupation du sol (OS) dans la zone écologique de la savane soudanaise, au nord-ouest du Nigéria. La recherche a analysé des images Landsat multitemporelles (2004, 2014 et 2024) afin de quantifier les tendances passées et d'établir des scénarios futurs pour 2035, 2045 et 2055. Une approche de classification supervisée a été utilisée pour générer les cartes d'occupation du sol, tandis qu'une modélisation CA-Markov, intégrée au plugin MOLUSCE de QGIS, a servi aux projections futures. La performance du modèle a été rigoureusement validée à l'aide des courbes d'apprentissage des réseaux de neurones et de l'analyse multirésolution de Pontius. Les résultats ont révélé une augmentation constante des surfaces dénudées, passant de 50,7 % en 2004 à 53,36 % en 2024, avec une diminution correspondante du couvert végétal, de 48,56 % à 45,77 %. Les projections indiquent une perte de végétation continue et accélérée, les surfaces dénudées devenant largement prédominantes d'ici 2055, notamment dans les parties centrale et orientale de la zone d'étude. Cette étude apporte des preuves crédibles et spatialement explicites de la dégradation continue des terres et des activités anthropiques dans la zone de savane soudanaise. Les résultats soulignent l'urgence de mettre en œuvre des stratégies de gestion durable des terres, de reboisement et d'adaptation au changement climatique afin d'atténuer les risques environnementaux projetés et de renforcer la résilience dans le nord-ouest du Nigéria.

Mots-clés: Utilisation des terres, Couverture terrestre, CA-Markov, Savane soudanaise, Nord-ouest du Nigéria, Changement climatique

INTRODUCTION

Climate change is one of the most critical global environmental concerns of the 21st century (Intergovernmental Panel on Climate Change [IPCC], 2022). Climate is dynamic, characterized by variations in temperature and precipitation over long periods (IPCC, 2021). It poses a severe threat to the environment, leading to rising temperatures, significant risks to vegetation, land degradation, prolonged droughts, and increased evapotranspiration (IPCC, 2022). In West Africa, and particularly in Nigeria, climatic conditions are increasingly unstable, leaving the region vulnerable to climatic shifts due to its diverse ecological zones (Okon et al., 2021).

The Sudan savannah ecological zone in Northwest Nigeria is highly vulnerable to anthropogenic activities and climatic variations. Because it lies within a semi-arid transition belt characterized by low annual rainfall, it is particularly prone to drought, desertification, and vegetation loss (Jenneh, 2025). This zone supports rainfed agriculture, pastoralism, and biodiversity, yet it faces heightened risks from climate variability, including reduced crop yields, increased heatwaves, and soil degradation, as evidenced by modeling studies in areas like Kano and the broader northern Nigerian region (Yelong, 2023; Derrick et al., 2025). The woody components of the Sudan savannah comprise a mixture of evergreen needle-like or broad-leafed trees and shrubs consisting of annual or perennial species (Hutley & Setterfield, 2018). Ecosystems fitting this description have ambiguously been termed woodlands, rangelands, grasslands, or wooded grasslands (Adedibu et al., 2021).

Land use and land cover (LULC) changes represent some of the most critical environmental transformations affecting semi-arid and savannah landscapes worldwide. These transformations reflect the cumulative influence of demographic pressures, agricultural expansion, urban growth, and climatic variability on terrestrial ecosystems (Soaga & Oluyege, 2025). Furthermore, vegetation trends in the Sudan savannah show mixed patterns. Despite some greening trends linked to rainfall recovery in parts of the Sudano-Sahelian belt - including Northwest Nigeria - persistent browning and degradation in semi-arid sub-zones signal ongoing ecological stress, with Normalized Difference Vegetation Index (NDVI) declines correlated with increased drought frequency (Ayansina, 2023; Murtala, 2023; Schürmann, 2025).

These dynamics are further complicated by climate extremes, such as heatwaves and variable precipitation, which disrupt savannah vegetation health and ecosystem services across tropical Africa, including Nigeria's northern zones (Yelong et al., 2025; Bashariya et al., 2025). Yabo and Tambari (2025) stated that over the last three decades, the region has experienced widespread conversion of natural vegetation into croplands, grazing fields, and settlements, resulting in severe land degradation, declining biomass productivity, and rising vulnerability to desert encroachment.

The study area is a critical agro-ecological region where climate variability has become more pronounced over recent decades, presenting complex challenges that remain inadequately understood and poorly quantified at a localized level (Emmanuel, 2022). It is characterized by semi-arid conditions, with an annual rainfall of 600–1,000 mm and mean temperatures of 28–32°C, supporting rainfed agriculture, grazing, and biodiversity (Kabir, 2024; Madaki, 2024). Recent studies show that the Sudan savannah ecological zone in Northwest Nigeria is currently undergoing rapid and extensive land changes driven by agricultural expansion, population growth, fuel-wood extraction, grazing pressure, and infrastructural development (World Bank, 2022). These processes have accelerated vegetation loss, soil degradation, declining agricultural productivity, and heightened susceptibility to desertification (Yabo & Tambari, 2025).

Consequently, this zone is becoming increasingly vulnerable to climate change. Key stressors include temperature rise, rainfall variability, desertification, frequent droughts, vegetation cover loss, and soil degradation, which collectively aggravate environmental degradation, reduce agricultural productivity, and threaten socio-economic stability (African Group of Negotiators Experts Support [AGNES], 2020; United Nations Convention to Combat Desertification [UNCCD], 2021).

Vegetation cover loss is evident through persistent browning and degradation in semi-arid sub-zones, including NDVI declines correlated with increased drought and heat stress that impact biodiversity and grazing lands (FAO, 2019; UNCCD, 2021; World Bank, 2022). Soil degradation, exacerbated by a projected 14 - 24% increase in rainfall-runoff erosivity over the coming decades in the Lower Niger Basin, results in topsoil depletion, reduced arable land, and salinization, further threatening food security (AGNES, 2020; Sahara and Sahel Observatory [OSS], 2024). Desertification also poses a severe threat, with risks of losing about 30 hectares of cropland per year in adjacent Sahel regions. This is driven by advancing arid conditions and contributes to declining forest resources and reduced vegetation cover in the Sudan savannah (AGNES, 2020; UNCCD, 2021; Madaki, 2024). Drought frequency has increased, with multi-year events becoming more common, leading to marked reductions in water body flow rates and network lengths, decreased soil fertility, and intensified water shortages in Northwestern Nigeria (United Nations Development Programme [UNDP], 2022). These interconnected variables could lead to a 20–30% reduction in agricultural yields by mid-century if left unmitigated, intensifying vulnerabilities for smallholder farmers and pastoralists, particularly women, who face disproportionate impacts on livelihoods and resource access (Ayodele, 2024; Philip et al., 2024; Timothy & Aruna, 2025).

Kabir et al. (2024) observed that the local population faces severe threats to their livelihoods and environment, specifically through declining crop yields caused by drought, extreme temperatures, and excessive evapotranspiration. Additionally, the study area has experienced the adverse effects of climate change on its rich biodiversity.

Despite these challenges, there appears to be limited attention given to comprehensive, spatially explicit assessments that integrate long-term vegetation dynamics to quantify exposure, sensitivity, and adaptive capacity in the Sudan savannah (World Bank, 2020, 2022). This research addresses these gaps by analyzing vegetation dynamics over the 1994 - 2024 period and assessing long-term LULC trends from 2035 to 2055 through an integrated vulnerability index model. Hence, the specific objectives are to analyze vegetation dynamics in the study area from 2004 to 2024 and to project future LULC changes from 2035 to 2055.

MATERIALS AND METHOD

Study Area

The Sudan savannah belt is situated in the northern part of Nigeria, located between latitudes 11°N and 13°N, and longitudes 7°E and 10°E (Figure 1). It stretches from the Sokoto Plains through the northern section of the High Plains of Hausaland to the Chad Basin. This belt spans over a quarter of the country's total land area, encompassing regions within Sokoto, Kebbi, Zamfara, Katsina, Kaduna, Kano, Jigawa, Yobe, and Borno States. Annual rainfall ranges from 600 to 1,000 mm, while the relative humidity remains generally below 40% except during the brief rainy months when it can exceed 60%. Diurnal temperatures fluctuate drastically, dropping to 15°C at night and exceeding 40°C during the day. Structurally, the subsoils frequently exhibit a clayey texture overlaid by sandy to loamy topsoils. When coupled with high-intensity rainfall events, these soil profiles render the region highly susceptible to erosion. Consequently, high rainfall variability, frequent droughts, and poor inherent soil fertility constitute major biophysical constraints to agriculture in this zone (Abaje et al., 2018).

The climate is characterized by four distinct seasons, beginning with the dry and cool season from mid-November to late February, which features the lowest ambient air temperatures of the year. This is followed by the dry and hot season from March to mid-May, a period marked by intense thermal conditions. The wet and warm season spans from late May to October and accounts for over 90% of the total annual precipitation. Finally, the dry and warm season commences immediately after the cessation of the rains in late October, lasting until mid-November as it transitions into the onset of the Harmattan dust winds.

The mean annual temperature is approximately 27°C, with peak temperatures (around 40°C) typically occurring in April and May, whereas the coolest period spans from December to February (Nigerian Meteorological Agency [NiMet], 2015). Evapotranspiration rates remain high throughout the year, peaking during the dry season. The typical soils are light brown, sandy, and reddish with medium fertility, making them physically easy to cultivate. The local flora is characteristic of the Sudan–Sahelian transition zone, which extends across the northernmost stretches of Nigeria, including Sokoto, Katsina, Kano, and Borno States (Ati et al., 2022; Abaje, 2023).

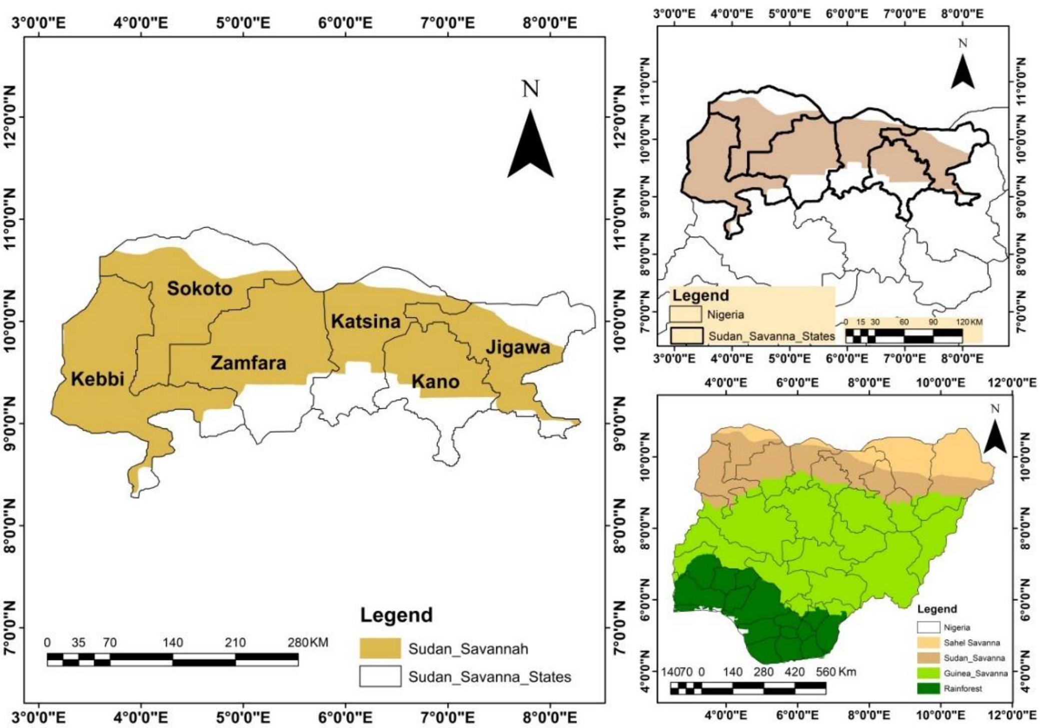


Figure 1: The Study Area

The satellite data used in this study consist of multi-temporal Landsat imagery sourced from the United States Geological Survey (USGS) EarthExplorer portal. The dataset includes Landsat-5 Thematic Mapper (TM) for 2004, Landsat-7 Enhanced Thematic Mapper Plus (ETM+) or Landsat-8 Operational Land Imager (OLI) for 2014, and Landsat-8/9 Operational Land Imager and Thermal Infrared Sensor (OLI/TIRS) images acquired in 2024. All images possess a spatial resolution of 30 meters and were selected from the same dry-season window to ensure consistent phenological conditions across the two-decade study period, thereby enabling reliable detection and analysis of land use and land cover (LULC) changes in the Sudan savannah ecological zone of Northwestern Nigeria.

Supervised image classification was executed to extract thematic land cover information from stacked multi-band raster composites (Figure 2). The classification process involved a systematic series of steps: identifying distinct features within the area of interest, selecting optimal input spectral bands, and generating training samples from verified ground-truth and reference locations representing the desired informational classes. Subsequently, spectral signature files were developed, evaluated, and edited where necessary before executing the classification algorithm. The target LULC schema was categorized into distinct classes, including dense vegetation, sparse vegetation, built-up/urban infrastructure, water bodies, bare soil, and agricultural land. This pixel-based classification approach systematically assigns every grid cell in the image matrix to a specific feature class based on its spectral properties (Olofsson, 2020).

Cellular Automata and LULC Projections

Cellular Automata (CA) modeling was utilized to simulate and predict future LULC transitions based on historical spatial trends and environmental driving forces. CA models simulate landscape evolution by applying defined transition rules to individual grid cells, governed by neighborhood interactions and land suitability factors. This study deployed the Modules for Land Use Change Evaluation (MOLUSCE) plugin, which integrates machine learning algorithms with CA frameworks to model complex land-cover dynamics. To initialize the CA model, classified LULC maps from at least two distinct historical periods are required, alongside spatial driver variables such as elevation, slope, distance to roads, distance to settlements, and Normalized Difference Vegetation Index (NDVI) values. These drivers account for the documented impacts of topography, accessibility, and anthropogenic pressure on land degradation and urban expansion patterns (Kamusoko, 2021; Mustafa, 2021).

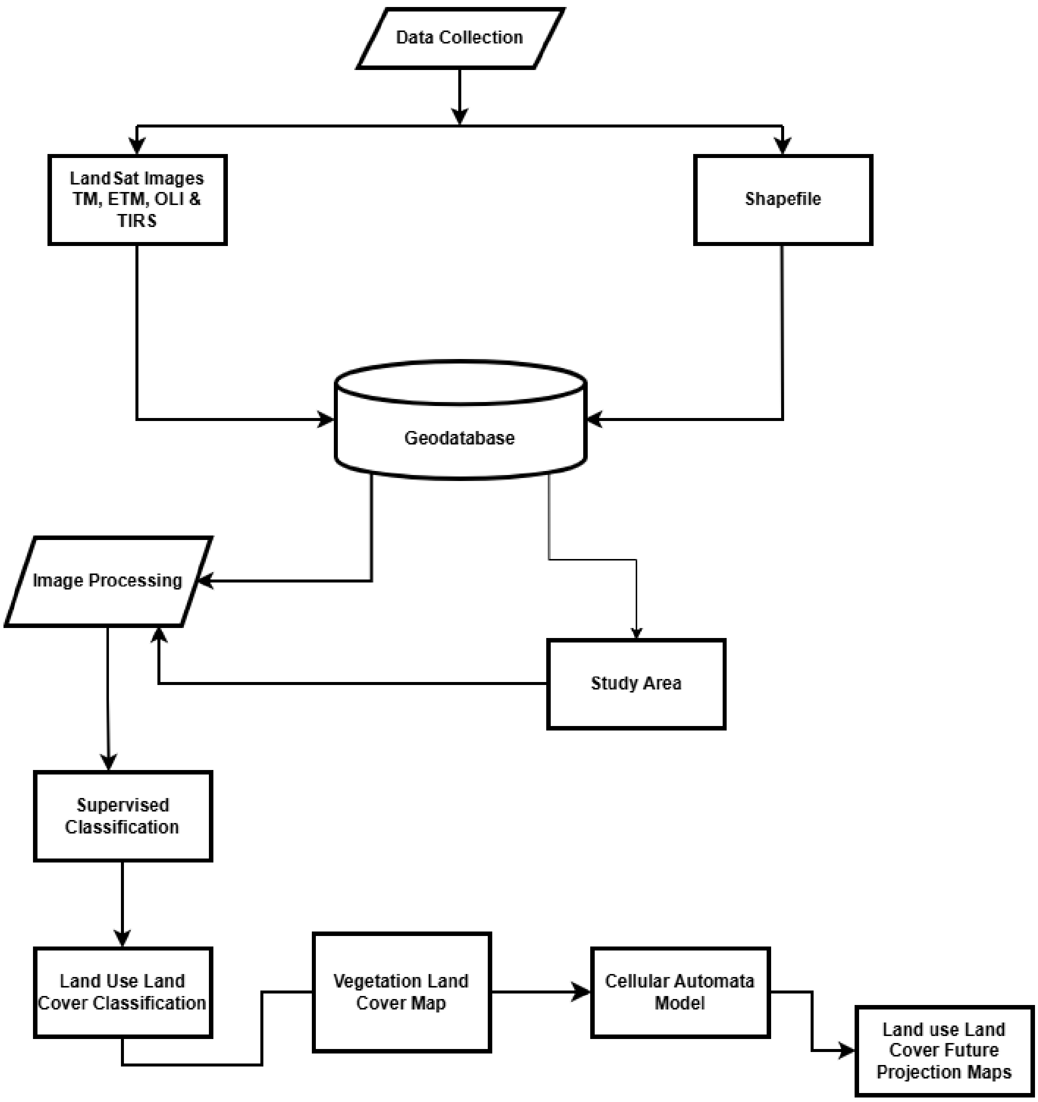


Figure 2: Methodological Flow Chart

RESULTS AND DISCUSSION

Land Use Land Cover Change from 2004 to 2024

Figure 3 shows the land use land cover for 2004 across the Sudan savanna in the Northwest Nigeria. Bare surfaces constituted the largest proportion of the study area, covering approximately 58,546.75km². This extensive presence of bare land indicates significant exposure of soil surfaces, which may be associated with sparse vegetation cover, seasonal dryness, and ongoing land degradation processes typical of the Sudan Savanna region. Vegetation covered approximately 56,015.50km², representing the second most dominant land cover class. The vegetation distribution was more concentrated in the western and southwestern parts of the study area, indicating relatively favorable environmental conditions such as higher soil moisture availability and less anthropogenic disturbance. However, the fragmented pattern of vegetation in other parts of the region suggests increasing pressure from agricultural expansion, grazing activities, and fuel-wood extraction. Built-up areas occupied approximately 2,194.50km²), representing a relatively small proportion of the total land area in 2004. These areas were mainly concentrated around urban centers and settlement clusters, indicating limited urban expansion at the time.

The results reflect the relatively low level of infrastructural development and population concentration within the region during the study period. Water bodies accounted for only 16,650 hectares (1656.50km²km²), making them the least dominant land cover class. The limited spatial extent of water bodies is consistent with the climatic characteristics of the Sudan Savanna ecological zone, which is characterized by low and highly seasonal rainfall. The sparse distribution of surface water resources highlights the vulnerability of the region to water scarcity and environmental stress.

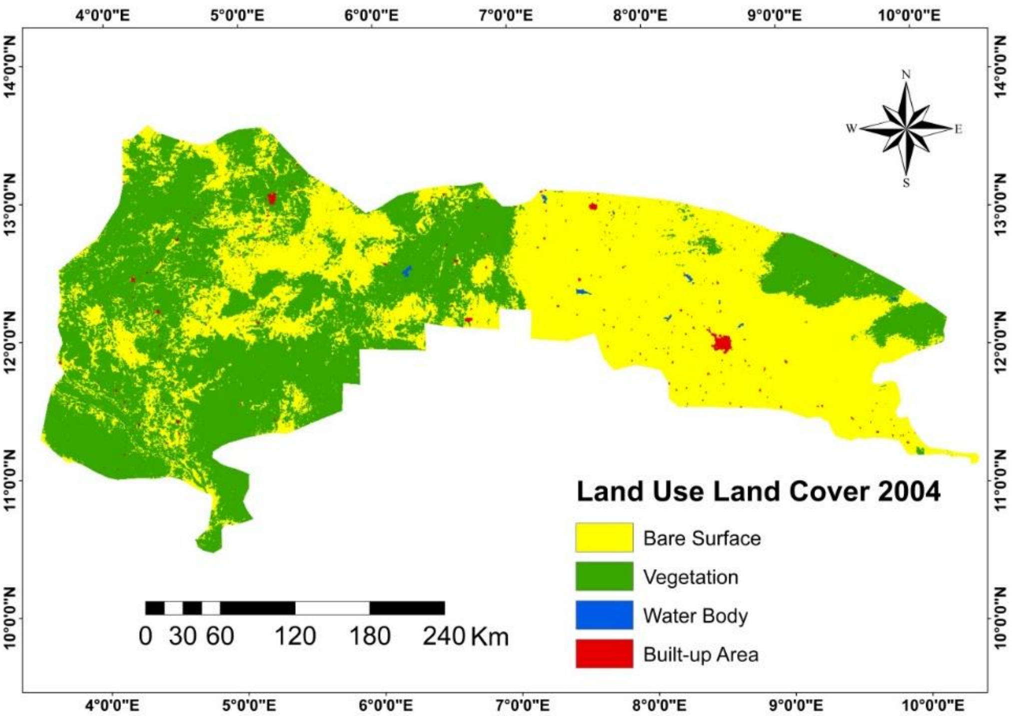


Figure 3: Land Use Land Cover 2004

Similar research stated that thick forest decreases throughout the year while open spaces or barren land increases subsequently in progressive period. These indicate the negative impact of desertification on vegetation cover in the study area (Hussaini, 2019).

The Land Use Land Cover (LULC) distribution of the study area in 2014 reveals a landscape dominated primarily by vegetation and bare surface, with minimal coverage by built-up areas and water bodies (Figure 4). The total mapped area covers approximately 118,414.25km², representing the entire spatial extent of the study region. Vegetation constitutes the largest land cover class, occupying 57,684.50km², which represents 49.93% of the total land area. This indicates that nearly half of the study area remains under vegetative cover, including savanna grasslands, shrubs, and cultivated lands. The dominance of vegetation, particularly in the southern and southwestern portions of the study area, reflects relatively favorable environmental conditions such as higher rainfall availability, better soil moisture retention, and active agricultural practices.

Bare surface closely follows vegetation in extent, covering 56,812.75km^2, equivalent to 49.16% of the total area. The extensive presence of bare surfaces indicates widespread exposure of soil due to sparse or absent vegetation cover. This condition is characteristic of semi-arid environments and suggests the influence of environmental stressors such as desertification, prolonged dry seasons, overgrazing, deforestation, and unsustainable land use practices. The spatial concentration of bare surfaces in the northern and northeastern parts of the study area reflects increasing aridity and land degradation intensity toward these regions. Built-up areas occupy 746.50 km², accounting for only 0.66% of the total land area. This relatively small proportion indicates that urban development remains spatially limited and concentrated in specific locations, mainly around major settlements and urban centers. Although currently minimal, the presence of built-up areas reflects ongoing human expansion, which may increase in the future and contribute to land cover transformation. Water bodies represent the smallest land cover category, covering only 2237.50km^2, equivalent to 0.17% of the total study area. This extremely low coverage reflects the semi-arid climatic conditions of the region, characterized by limited permanent surface water. The spatial distribution of water bodies is fragmented, consisting mainly of small reservoirs and seasonal water sources.

The land use and land cover distribution in 2024 shows that bare surface is the dominant land cover class, occupying 62,220.69km² (53.36%) of the total study area (Figure 5). This indicates a substantial extent of exposed soil and sparsely vegetated land, particularly in the northern and central portions of the study area. The dominance of bare surfaces reflects increasing environmental stress, possibly linked to land degradation, desertification processes, and prolonged anthropogenic pressure such as overgrazing and unsustainable land use practices. Vegetation represents the second largest land cover category, covering 53,487.19km² (45.77%). These areas are concentrated mainly in the southern and southwestern portions of the study area, where climatic and soil conditions are relatively more favorable for plant growth. However, the proportion of vegetation is lower than bare surface, suggesting a gradual decline in vegetative cover and reduced ecological resilience in the region.

Built-up areas occupy 1645.19km² (0.69%), indicating relatively limited but steadily increasing urban expansion.

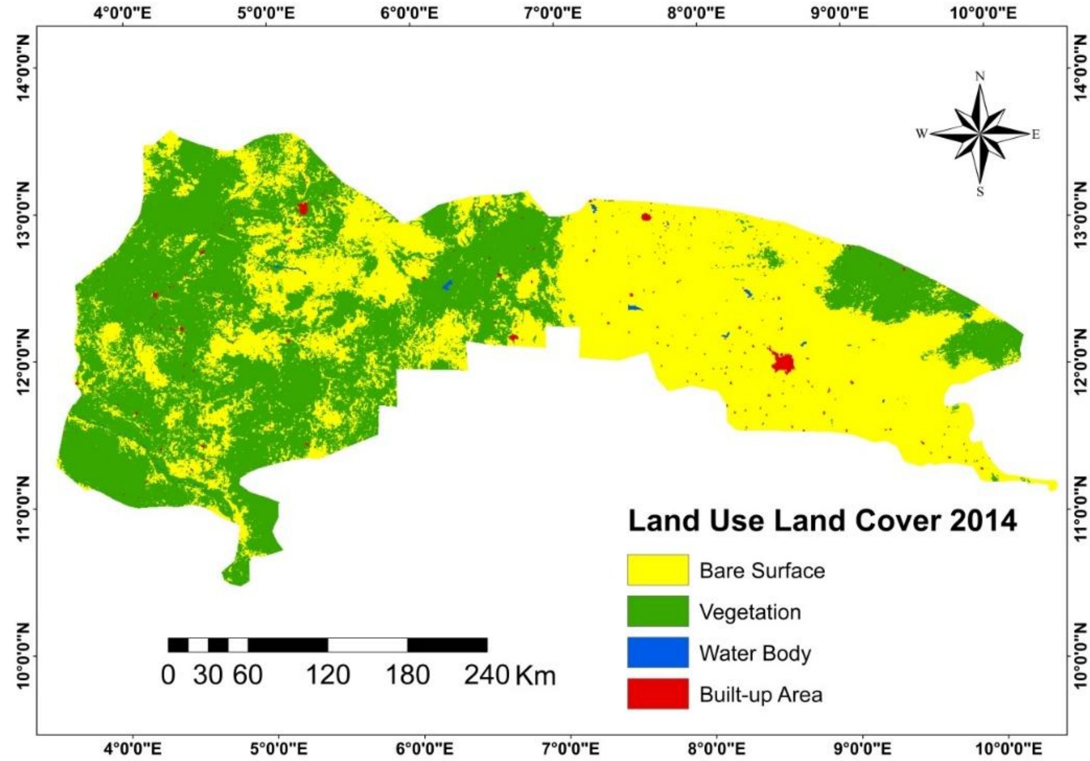


Figure 4: Land Use Land Cover 2014

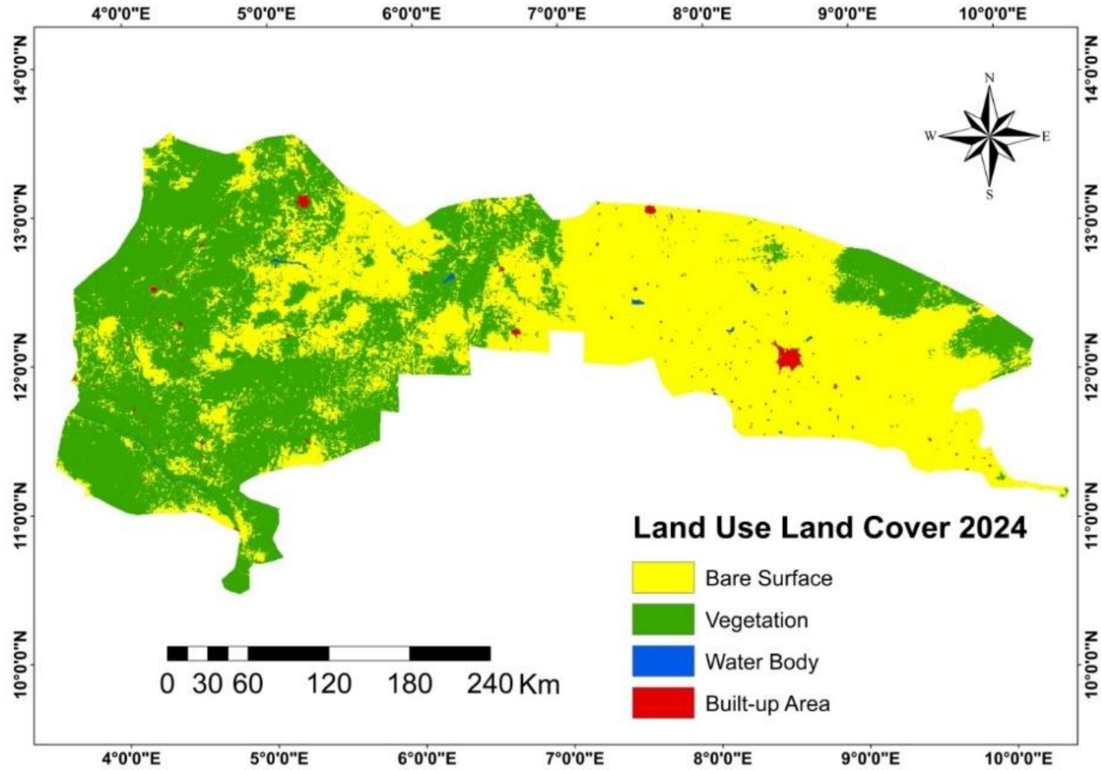


Figure 5: Land Use Land Cover 2024

These areas are primarily concentrated around major urban centers, reflecting population growth, infrastructure development, and increasing socioeconomic activities. Although the spatial extent is small compared to natural land cover classes, the growth of built-up areas has significant implications for land transformation and ecosystem disruption. Water bodies account for the smallest proportion, covering only 1061.19km² (0.18%). These include rivers, reservoirs, and small inland water features scattered across the study area. The limited spatial coverage of water bodies reflects the semi-arid climatic conditions of the Sudan Savanna ecological zone where surface water availability is naturally constrained.

Land Use Land Cover Future Projection 2035 to 2055

Land Use Land Cover Future Projection 2035

The projected Land Use Land Cover (LULC) map for 2035 indicates a clear intensification of environmental change across the Sudan Savanna ecological zone (Figure 6). The most striking pattern is the expansion of bare surface, which dominates a substantial portion of the central, northern, and eastern regions. Compared to earlier periods (2004 - 2024), this represents a continued trajectory of land degradation and vegetation loss.

Vegetation will be largely confined to the southern and southwestern parts of the study area, with noticeable fragmentation in the central zones. This spatial contraction of vegetation suggests declining ecological resilience and reduced primary productivity. The fragmentation pattern also indicates that vegetated areas are becoming increasingly isolated, which can negatively affect biodiversity and ecosystem stability. While built-up areas, although still relatively small in areal extent, show increased clustering and expansion around urban centers, particularly in the central-east. This reflects ongoing population growth and land transformation processes, which further contribute to vegetation clearance and soil exposure. Water bodies remain sparse and discontinuous, reinforcing the inherent hydrological limitation of the region.

The neural network learning curve provides insight into the training dynamics and predictive performance of the model used in the LULC simulation (Figure 7). It is observed that the training loss (green) remains consistently low, indicating effective learning of spatial patterns. On the other hand, the validation loss (red) is slightly higher and exhibits fluctuations, suggesting some level of variability in prediction accuracy. The absence of large divergence between training and validation curves indicates minimal overfitting and occasional spikes in validation error may reflect the spatial heterogeneity in land cover transitions and influence the external factors such as climate variability and human activities.

The multiple-resolution budget graph demonstrates the performance of the model in simulating land cover change across varying spatial resolutions and information levels (Figure 8). Model performance improves progressively from no information to perfect information scenarios in which the highest accuracy (~0.95 - 1.0) is achieved under perfect location and quantity information, while the moderate performance (~0.50 - 0.60) under partial information reflects realistic modelling conditions. This indicates that the model is robust and sensitive to spatial information, with reliable predictive capability when sufficient input data are provided. The gradual improvement across resolution levels confirms the consistency of the modelling framework.

From a practical standpoint, this suggests that the projected increase in bare surface and decline in vegetation are not random but are systematically driven and reliably captured by the model.

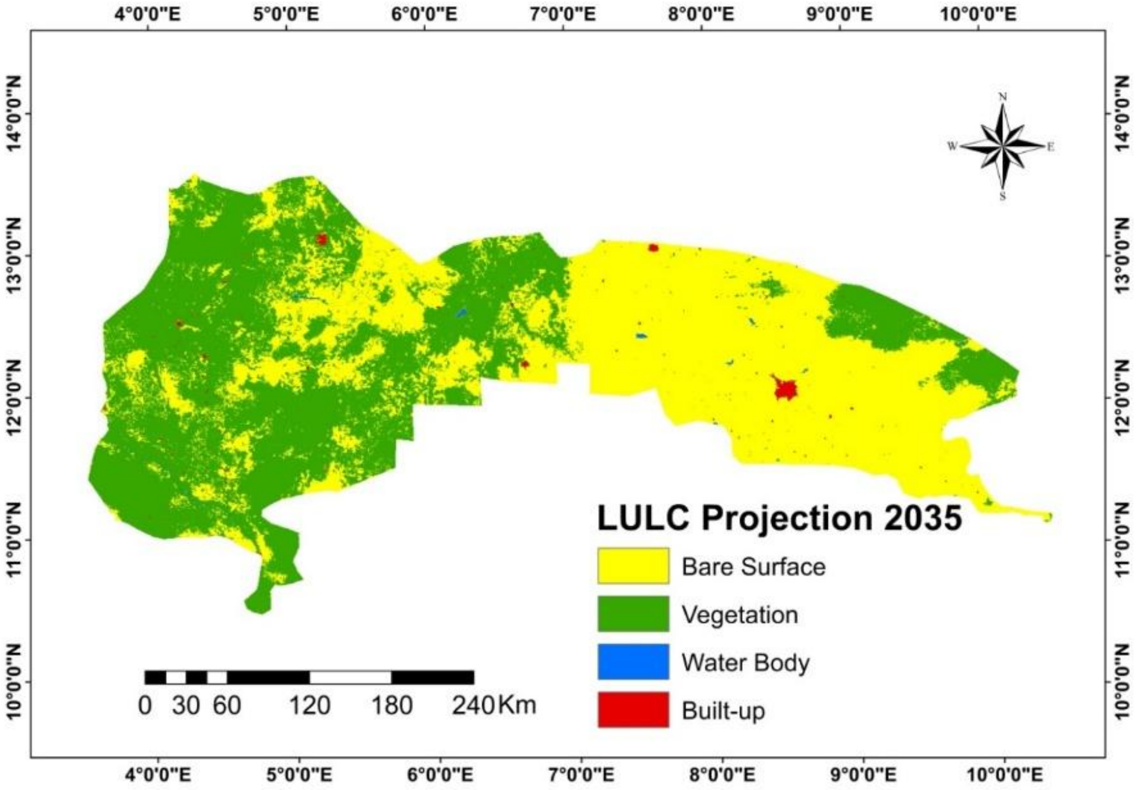


Figure 6: Land Use Land Cover Future Projection 2035

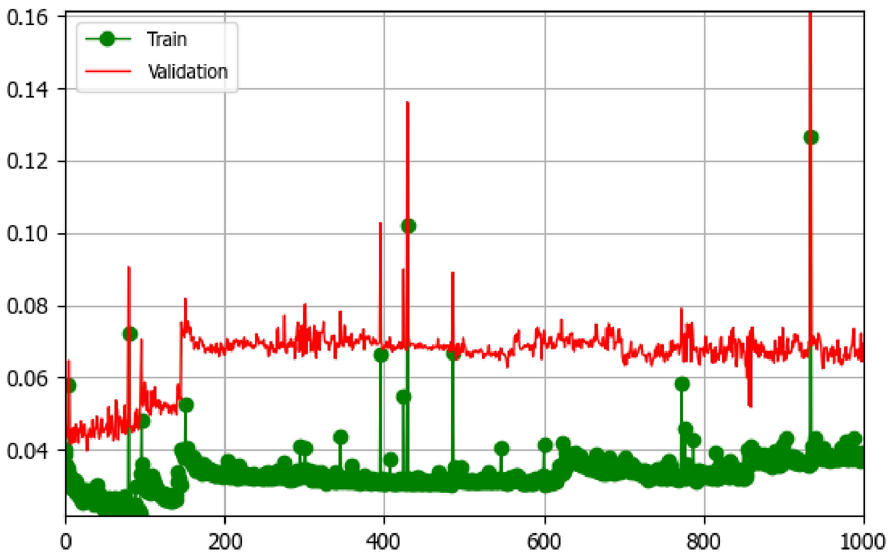


Figure 7: Neutral Network Learning Curve 2035

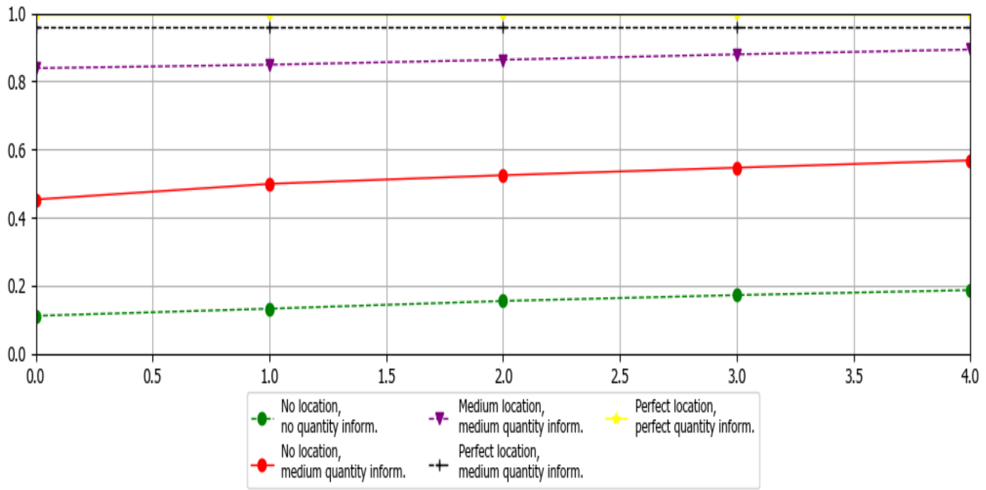


Figure 8: Multiple-resolution Budget 2035

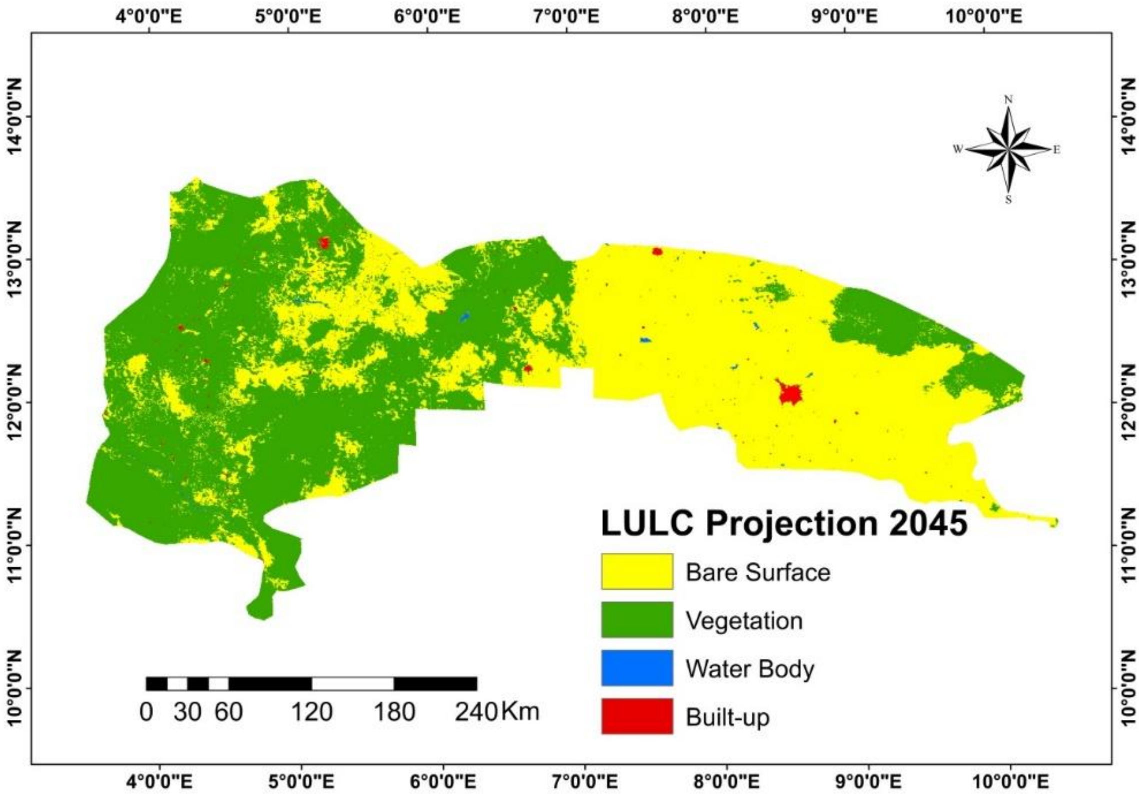
Land Use Land Cover Future Projection 2045

The projected Land Use/Land Cover (LULC) map for 2045 reveals the spatial pattern which indicates that bare surfaces dominate a substantial portion of the central and eastern regions of the study area (Figurer 9). These areas form large, continuous patches, suggesting extensive land exposure and reduced vegetation cover. The continuity of these zones indicates a strong spatial consolidation of bare land by 2045. In contrast, vegetation is predominantly concentrated in the western and northwestern regions, where it forms relatively dense and contiguous patches.

However, vegetation appears fragmented toward the central regions, where it transitions into bare surfaces, indicating a spatial gradient from vegetated to non-vegetated land cover. Built-up areas are sparsely distributed but show clear clustering in specific locations, particularly within the central and eastern parts of the study area. These clusters represent localized zones of urban expansion, although their overall spatial extent remains limited relative to other land cover classes. Water bodies are minimal in spatial extent and occur as small, scattered patches. Their distribution is highly localized, indicating that water features are not a dominant component of the landscape in the projected year.

The training loss (green) declined sharply from an initial value of approximately 0.13 to stabilize around 0.02–0.03 after 200 epochs (Figure 10), although occasional spikes were observed at later stages (approximately 600, 800, and 1000 epochs). The validation loss (red) exhibited moderate fluctuation but converged at lower values (approximately 0.025–0.035) with no pronounced upward trend. The limited and stable gap between training and validation losses indicates acceptable generalization and absence of severe over-fitting.

The validation demonstrates strong predictive capability (Figure 11). At the finest resolution, the curve for medium location and medium quantity information reaches agreement values of approximately 0.92–0.95, closely approximating the perfect information reference lines. The minimal divergence between the medium-information curve and the theoretical maxima indicates that the model accurately simulated both the quantity of transitions and their spatial allocation. The persistently low agreement under the no location, no quantity scenario confirms that model skill substantially exceeds random chance.



Figurer 9: Land Use Land Cover Future Projection 2045

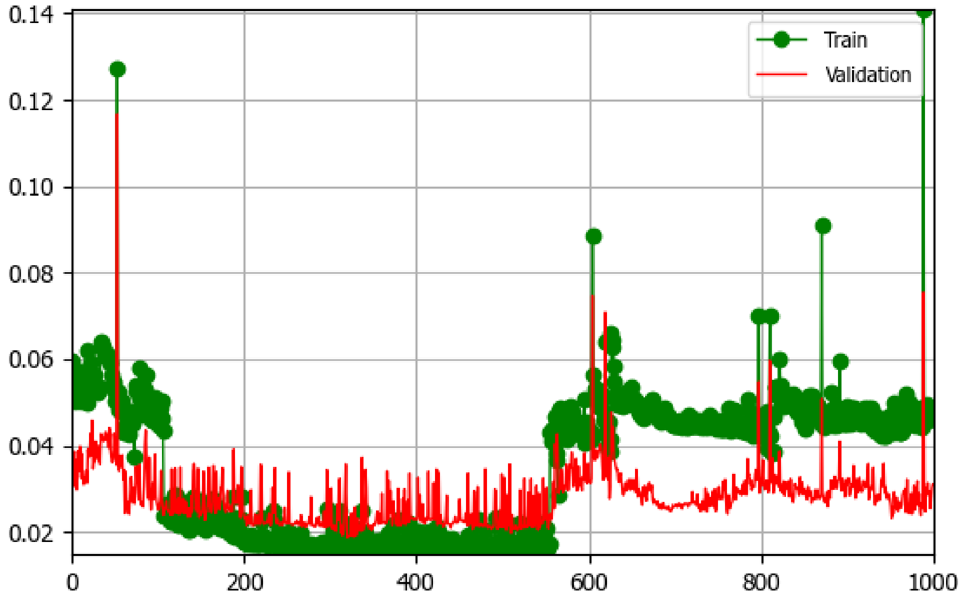


Figure 10: Neutral Network Learning Curve 2045

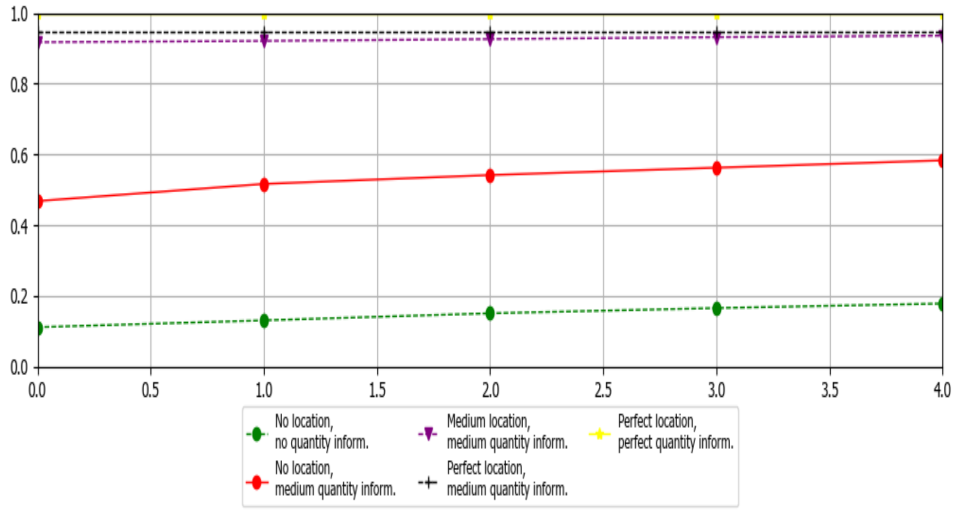


Figure 11: Multiple-resolution Budget 2045

Land Use Land Cover Future Projection 2055

The 2055 LULC projection indicates a significant transformation in the landscape composition (Figure 12). Bare surface emerges as the dominant land cover class, occupying extensive contiguous areas, particularly in the central and eastern sectors of the study region. Vegetation cover, while still present in the western portion and along fragmented patches in the north and south, shows a marked reduction compared to earlier baseline periods.

Built-up areas remain relatively limited and concentrated in isolated clusters, suggesting that urban expansion, though increasing, is not the primary driver of change in this projection. Water bodies appear minimal and scattered, consistent with the hydrological characteristics of the semi-arid environment.

This projected dominance of bare surface points to a continuing trend of vegetation loss and land degradation. Such a pattern is consistent with prevailing anthropogenic and climatic pressures in West African savanna and transitional ecosystems, including agricultural expansion, fuel-wood extraction, and reduced rainfall reliability.

The training loss decreased rapidly from an initial value of approximately 0.030 to below 0.005 within the first 200 epochs and stabilized at very low levels thereafter (Figure 13). The validation loss exhibited greater initial fluctuation but converged around 0.015–0.017 after 600 epochs, with no evidence of substantial over-fitting. The modest and stable divergence between training and validation losses indicates good generalization capability of the network. This successful training outcome confirms that the selected driving factors (including proximity to settlements and roads, topographic variables, population density, and climatic variables) provided sufficient explanatory power for modelling LULC transitions.

The multiple-resolution budget 2055 analysis reveals strong model performance (Figure 14). At the finest resolution (0 km), the model incorporating medium location and medium quantity information achieved agreement levels approaching 0.92–0.95, closely tracking the theoretical perfect-information curves. The minimal gap between the "medium location, medium quantity" curve and the perfect lines, even at finer resolutions, demonstrates that the model accurately captured not only the overall quantity of land cover transitions but also their spatial allocation. The low baseline agreement under "no location, no quantity" conditions further confirms that the observed high performance is attributable to the model's predictive power rather than chance.

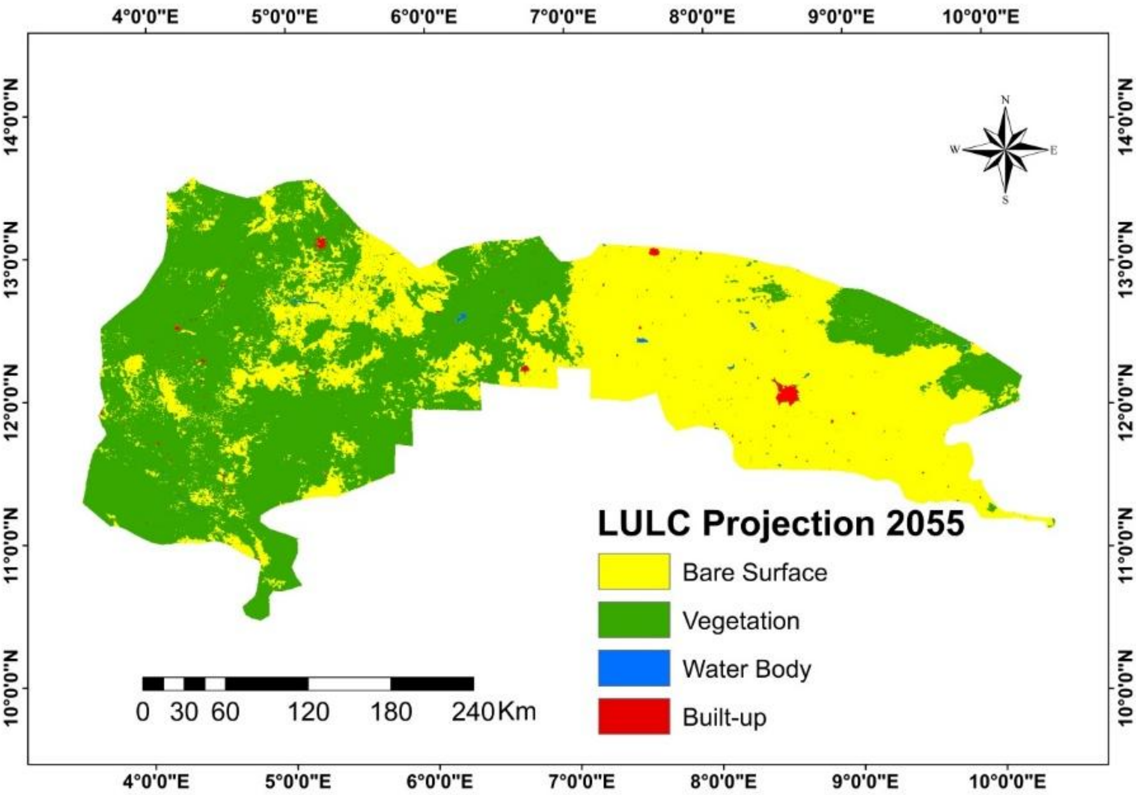


Figure 12: Land Use Land Cover Future Projection 2055

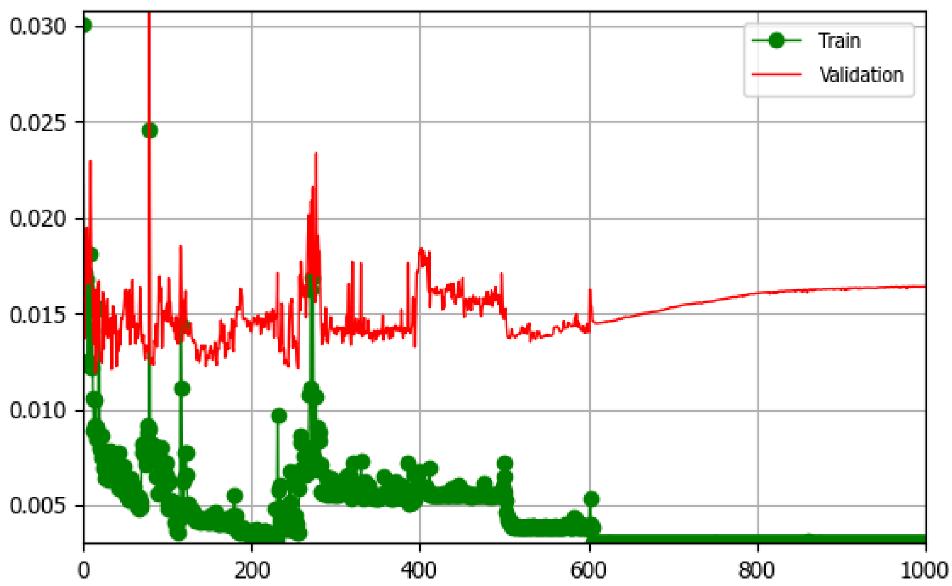


Figure 13: Neutral Network Learning Curve 2055

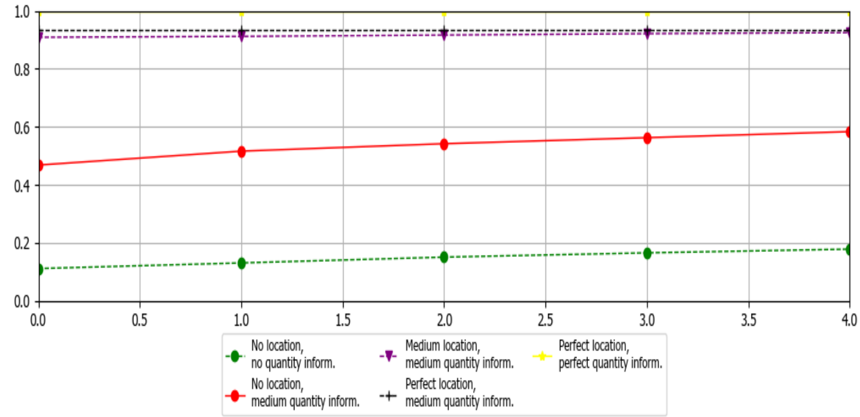


Figure 14: Multiple-resolution Budget 2055

CONCLUSION

This study modelled changes in Land Use/Land Cover (LULC) in the Sudan Savanna ecological zone of Northwestern Nigeria from 2004 to 2024 and projected future scenarios to 2055 using an integrated Cellular Automata–Markov (CA-Markov) framework driven by Multi-Layer Perceptron Neural Networks. Historical LULC analysis revealed a persistent dominance of bare surface, which increased from 50.70% in 2004 to 53.36% in 2024, while vegetation cover declined from 48.56% to 45.77% over the same period. Built-up areas showed modest growth from 0.60% to 0.69%, and water bodies remained minimal at less than 0.20% of the study area. The 2035, 2045, and 2055 LULC projections consistently indicate a continuing and accelerating trend of vegetation loss and bare surface expansion, particularly in the central and eastern sectors of the study area. By 2055, bare surface is projected to become overwhelmingly dominant, with vegetation largely confined to fragmented patches in the western and southern fringes. Built-up expansion remains secondary to vegetation-to-bare conversion. Policymakers should prioritize large-scale reforestation and agroforestry programmes, particularly in the high-degradation zones identified in the projections, to reverse vegetation loss. It is also recommended to develop and enforce integrated land-use master plans that regulate agricultural expansion and urban growth to minimize further vegetation conversion.

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