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Time Series Analysis of Satellite Data to Characterize Multiple Land Use Transitions: A Case Study of Urban Growth and Agricultural Land Loss in Lusaka

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Abstract

The rapid evolution of land use patterns in Lusaka presents significant challenges for sustainable urban development and resource management. This study employs a time-series analysis of satellite imagery to examine the spatial and temporal dynamics of land use transitions from 1992 to 2024. The research focuses on identifying urban expansion trends, agricultural land loss, and the socio-economic and environmental drivers influencing these changes. By integrating advanced remote sensing techniques and Geographic Information System (GIS) methodologies, the study provides a detailed assessment of land cover transformations and their implications for urban planning. Using a multitemporal dataset of high-resolution satellite images, the study applies cutting-edge image classification algorithms and change detection techniques to generate land cover maps and quantify urban growth. The findings reveal a significant increase in built-up areas at the expense of agricultural land and natural vegetation, highlighting the pressures of population growth, rural-urban migration, and economic policies on land use transitions. Additionally, weak land tenure systems and inconsistent policy enforcement have contributed to the unregulated conversion of agricultural land for urban purposes. Beyond spatial analysis, the study incorporates socio-economic indicators such as demographic changes, infrastructure investments, and policy interventions to contextualize urban expansion trends. Statistical modeling and spatial analysis techniques further identify key drivers of urbanization, including rapid population growth, increased commercial development, and inadequate land governance mechanisms. The results of this study provide valuable insights for policymakers, urban planners, and land managers in developing sustainable strategies to mitigate the adverse effects of uncontrolled urban expansion. Recommendations include strengthening land governance, enforcing zoning regulations to protect agricultural land, and promoting environmentally sustainable urban development practices. Additionally, the methodological framework developed in this research can be applied to other rapidly urbanizing regions facing similar land use challenges.

Keywords

Time Series Analysis, Satellite Data, Urban Growth, Image Classification, Change Detection

1. Introduction

Lusaka is one of the most urbanised cities in Zambia with a population estimated at over 2 million people. According to the Zambia Statistics Agency, between 2010 and 2022, Lusaka had an average annual population growth rate of 2.0%. Increases in the urban population promote further urban expansion, which has been recognized as a highly significant human-induced disturbance and one of the main threats to the sustainability of natural resources [1].

Land use is a dynamic phenomenon that changes with time and space due to anthropogenic pressure and development [2]. Rapid urbanization and expanding human activities pose significant challenges to land management and sustainable development in many regions worldwide. The characterization and understanding of land use transitions, particularly in rapidly growing urban areas, are crucial for effective land use planning and resource allocation. Time series analysis of satellite data has become a potent instrument for examining land use dynamics and their consequential effects. This research study centers on employing time series analysis of satellite data to characterize various land use transitions in Lusaka, with a particular focus on urban growth and agricultural land loss. Utilizing high-resolution satellite images for examining the changes in use of land and landscape over time offers valuable insights into urban growth, expansion, and shifts in land utilization [1]. This data serves as a valuable resource for planning and managing human development and facilitating a comprehensive understanding of the urban landscape's overall transformation.

The increasing availability and volume of remote sensing data, such as Landsat satellite images, have allowed the multidimensional analysis of land use/land cover (LULC) changes [3]. By applying image processing techniques, including image classification and change detection, the research will extract meaningful information from the satellite data. Furthermore, the research will integrate ancillary data, such as socioeconomic indicators and population growth, to contextualize the observed land-use transitions and identify the underlying drivers.

This research study aims to employ advanced remote sensing and geospatial analysis techniques to characterize the multiple land-use transitions taking place in Lusaka. By utilizing satellite data, the research will investigate the temporal patterns of urban growth and land loss, identify areas of significant change, and assess the impacts on the landscape. The primary objective is to provide policymakers, urban planners, and land managers with valuable information that can support evidence-based decision-making for sustainable management of land use in Lusaka and Zambia as a whole.

This paper will explore the use of satellite data and geographic information systems to characterize multiple land use transitions in the city of Lusaka to understand the spatial changes and urban growth over specific time periods *i.e.*, 1992, 1999, 2009, 2019, 2023 and 2024. The findings of this research will enhance our comprehension of the intricate interactions between urban growth, agricultural land loss, and sustainable development in Lusaka. The study's outcomes will offer valuable insights that can inform evidence-based strategies for achieving a balanced and sustainable urban landscape in the city. The findings will inform land use planning, conservation efforts, and policy interventions aimed at mitigating the adverse effects of land use changes. Moreover, the methodology developed in this study can serve as a valuable framework for similar time series analyses of satellite data in other regions facing similar land use challenges.

In brief, this research study aims to employ time series analysis of satellite data to depict various land use transitions in Lusaka, with a primary focus on urban growth and agricultural land loss. By leveraging advanced remote sensing techniques, the researcher's objective is to gain valuable insights into the spatial and temporal patterns, underlying drivers, and consequences of these transitions. Ultimately, this research will contribute to sustainable management of land use and facilitate informed decision-making processes.

2. Study Area and Data

2.1. Study Area

Lusaka named after a Soli Headman known as Mwalusaka is the capital city of Zambia, one of the fastest developing cities in Southern Africa. In 1911 it became the capital of Northern Rhodesia what is today Zambia. It serves as an administrative center and commercial Centre for the Country. In addition to its role as Zambia's administrative capital, Lusaka is also the economic, cultural, and transportation center of the nation [4].

Lusaka district is located in the Lusaka province of Zambia and serves as both the provincial capital and the national capital city. **Figure 1** illustrates the city of Lusaka's location, which covers an approximate area of 418.77 square kilometers. Lusaka is located in the south-east of Zambia and the interior of the Central African plateau at an elevation of approximately 1300m above sea level.

Lusaka's Population in 2010 was 1,747,152 and the preliminary census population as at 2022 is estimated to be 2,204,059 [5].

2.2. Satellite Data

In this study, comprehensive satellite data was collected, including primary high-resolution images obtained from Google Earth Pro, enabling a detailed analysis of the study area. Additionally, the digital elevation model (DEM) sourced from the Shuttle Radar Topography Mission (SRTM) furnished invaluable information at a spatial resolution of 1 arc second, approximately 30 meters, enabling the extraction of elevation and slope data for the study area, Lusaka district.

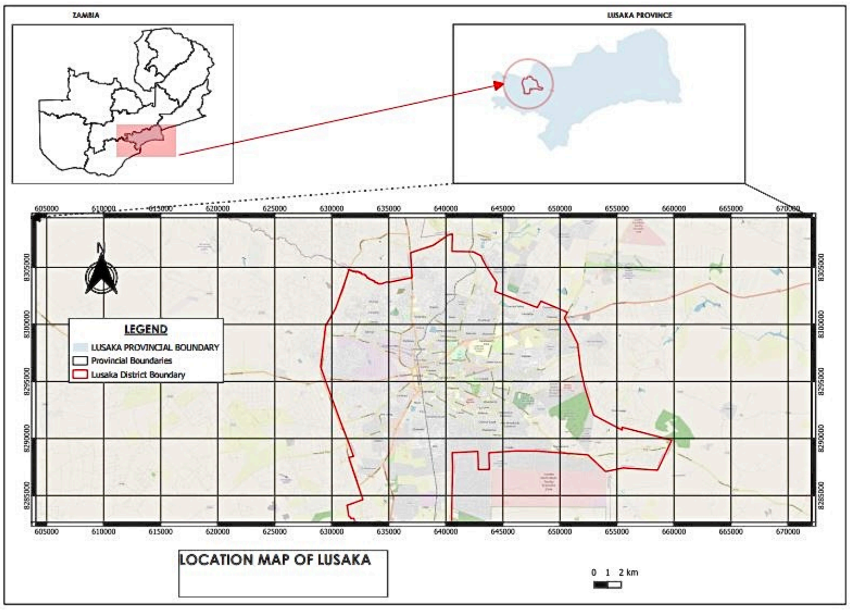


Figure 1. The geographical position of Lusaka District.

Furthermore, global annual land cover satellite imagery with a resolution of 300 meters was procured from the Climate Change Initiative (CCI) data repository. This dataset played a crucial role in analyzing land cover dynamics and changes over time in Lusaka. Incorporating additional ancillary data, the study enriched its analysis with a 1985 topographical map of Lusaka, offering historical context and aiding in tracking land cover transformations. Vector data, including district road datasets and the district boundary of the study area, provided essential geospatial information for precise spatial analysis and urban growth modeling.

This study adopted a robust and comprehensive approach by harnessing a diverse range of satellite imagery, ancillary data, and vector datasets. These combined resources enabled a thorough exploration and aimed to comprehend the intricate dynamics of land cover changes and urban growth within Lusaka district. The utilization of high-resolution data from Google Earth Pro, along with precise elevation and slope information from SRTM, and annual land cover satellite imagery from CCI, enabled a comprehensive investigation of urbanization processes. These data sources provided valuable insights that can inform sustainable urban planning and environmental management strategies in the region.

3. Literature Review

In this chapter, the researcher will delve into a comprehensive explanation of the concept of time series analysis and its practical application in the context of land use studies. The primary goal of this literature review is to furnish a comprehensive overview of the various methodologies employed and the significant findings related to this research topic. By exploring existing studies and research in the field of time series analysis of land use data, the researcher aims to consolidate the knowledge base and gain valuable insights into the changes and trends of the use of land over time. The literature review serves as a vital foundation for understanding the significance of time series analysis in characterizing multiple land use transitions and how it contributes to our understanding of urban growth, agricultural land loss, and other land use changes in Lusaka and similar regions.

3.1. Key Definitions

- **Time series analysis** is a statistical approach employed for analyzing and interpreting data gathered over sequential time intervals. Its objective is to investigate the patterns, trends, and interrelationships present within the data, enabling a comprehension of their temporal characteristics and facilitating predictions regarding future values. Time series analysis finds broad utilization in a range of disciplines, including economics, finance, weather forecasting, and remote sensing [6].
- **Image classification** is a process of categorizing pixels or image segments in a digital image into different predefined classes or categories. It involves the assignment of labels to pixels based on their spectral characteristics or other relevant features. Image classification is a fundamental technique in remote sensing, enabling the extraction of land cover information from satellite imagery. It plays a crucial role in applications such as land use mapping, change detection, and monitoring of natural resources [7].
- **Satellite data** refers to information captured by satellites orbiting the Earth. Satellites equipped with sensors and instruments collect data across different parts of the electromagnetic spectrum, including visible, infrared, and microwave wavelengths [6].

These data provide valuable information about various Earth processes, such as land cover, vegetation dynamics, atmospheric conditions, and oceanic patterns. Satellite data is extensively used in remote sensing applications for environmental monitoring, land use analysis, climate studies, and natural resource management.

- **Change detection** is the process of identifying and quantifying changes in land cover or land use between different time periods. It involves comparing and analyzing satellite images or other geospatial data captured at different time points to identify areas where land cover has undergone significant alterations [8]. Change detection techniques enable the detection of various types of changes, such as urban expansion, deforestation, agricultural land loss, or natural disasters. Geographic Information Systems (GIS) are indispensable tools in the realms of environmental monitoring, land management, and evaluating the consequences of land use alterations.

- **Urban growth** refers to the expansion and development of urban areas over time. It involves the physical expansion of built-up areas, the increase in population and infrastructure, and the transformation of natural or rural land into urbanized land [9]. Urban growth is a dynamic process influenced by factors such as population growth, migration, economic development, and urban planning policies. Comprehending urban growth patterns and dynamics is imperative to foster sustainable urban development, efficient land management, and effective urban planning.

3.2. A Case Study of Five Cities of Saudi Arabia

This particular case study investigated the analysis of urban land cover change and the modeling of urban growth in five significant cities of Saudi Arabia, namely Riyadh, Jeddah, Makkah, Al-Taif, and the Eastern Area. Time-series satellite images from 1985 to 2014 are employed, and remote sensing and geospatial analysis techniques were utilized to investigate the patterns and dynamics of urbanization within these cities. The analysis encompassed data preprocessing, image segmentation, classification, accuracy assessment, and land cover change modeling using the Markov Chain (MC) method. The findings offered valuable insights into the extent and direction of urban growth, shedding light on the challenges and implications for environmental management and future urban planning in the studied regions. The dynamics of urban growth and land cover change in Saudi Arabian cities carry substantial implications for environmental management, allocation of natural resources, and the promotion of sustainable urban development. This case study focused on five significant cities in Saudi Arabia and aimed to analyze the urban land cover change patterns, model the urban growth, and understand the underlying factors driving the changes. The study used time-series satellite images and applied remote sensing and geospatial analysis techniques and provided valuable insights into the dynamics and impacts of urbanization in these aforementioned cities.

The study made use of Landsat thematic mapper (TM), enhanced thematic mapper plus (ETM+), and operational land imager (OLI) images collected from the United States Geological Survey (USGS) Global Visualization (GloVis) site. The images from 1985 to 2014 were subjected to data preprocessing, including georeferencing, image-to-image registration, and image subset extraction. Image segmentation and classification were performed using Cognition Developer 8.9 software, applying object-based image analysis (OBIA) techniques [10].

Accuracy assessment was conducted to evaluate the classification results using reference data obtained from stratified random sampling. Land cover change modeling was accomplished using the Markov Chain (MC) method, which generated transition probability and transition area matrices.

The accuracy assessment of the land cover classifications revealed high overall accuracies, ranging from 82% to 96%, for the five cities. The land cover change analysis revealed varying patterns of urban growth and land cover conversions across the study period. The transition probability matrices indicated that bare soil (BS) was the most converted land type, followed by vegetation cover (VC) and water (W) transitioning to urban areas (UA). The transition suitability maps, integrating variables like elevation, slope, distance from drainage, distance from roads, and distance from urban cover, offered valuable insights into the spatial determinants of land cover changes and urban growth in the study areas.

3.3. Lessons Learnt from the Case Study

The case study's findings shed light on the noteworthy urban growth and land cover transformations experienced in the five cities of Saudi Arabia over the period from 1985 to 2014. Through the analysis of time-series satellite images, this research has provided significant insights into the patterns and evolution of urban land cover change in cities across Saudi Arabia. The studies have underscored the swift and extensive enlargement of urban regions, leading to the encroachment on agricultural land and the consequential environmental and socio-economic ramifications.

The results highlight the importance of adopting sustainable urban planning practices to address the challenges posed by rapid urbanization. As urban areas continue to expand, there is a growing need for well-designed green infrastructure initiatives to preserve natural ecosystems, enhance resilience to environmental pressures, and improve the overall quality of life for residents. Furthermore, effective land management strategies are essential to strike a balance between urban development and the conservation of valuable agricultural lands.

The lessons learned from these studies underscore the significance of proactive and forward-thinking policies aimed at managing urban growth and land use changes in a sustainable and responsible manner. By integrating environmental considerations, social equity, and economic viability into urban planning decisions, cities can strive towards a more resilient and harmonious urban landscape. These findings act as crucial guidance for policymakers, urban planners, and stakeholders in shaping the future of Saudi Arabian cities and fostering a balanced and sustainable urban environment.

4. Methodology

This research utilizes a multi-temporal dataset of satellite imagery, specifically updated Landsat and Sentinel-2 imagery, to capture the temporal dimension of land use transitions in Lusaka from 1992 to 2024. The updated dataset ensures a more accurate and relevant analysis, reflecting the latest urbanization and land cover changes. The integration of Sentinel-2 imagery, with its higher spatial resolution (10 m), addresses limitations posed by the previously used 300 m resolution, allowing for finer detection of urban expansion and agricultural land loss.

The decision to use Landsat and Sentinel-2 imagery stems from their well-established reputation as reliable remote sensing data sources. Their long-term data archives enable researchers to assess trends in urban growth and land use modifications over multiple decades. By analyzing satellite images from 1992 to 2024, this study provides a comprehensive view of urbanization patterns and their socio-economic and political drivers. Unlike previous studies that solely focused on spatial expansion, this research incorporates policy decisions, economic developments, and population growth trends that have influenced land use changes.

A key methodological innovation in this study is the application of a hybrid classification approach, combining pixel-based and object-based image analysis (OBIA). This enhances accuracy by considering spatial, spectral, and contextual attributes of land cover types. Preprocessing steps, including radiometric calibration, atmospheric correction, and image registration, ensure the consistency and reliability of the data. Data fusion techniques are employed to integrate Landsat and Sentinel-2 datasets, improving the spatial and temporal resolution.

Furthermore, this study examines the socio-economic and political drivers of urban expansion and agricultural land loss in Lusaka. It assesses the role of government policies, infrastructure development, land tenure systems, and population pressure in shaping land use dynamics. By integrating statistical and spatial analysis, this research moves beyond simple urban growth mapping to provide deeper insights into the forces driving land cover changes.

4.1. Land Cover Classification

Figure 2 shows process structure from data acquisition to interpretation and visualization. Land cover classification techniques are essential for mapping and analyzing land use changes over time. This study employs a supervised classification approach using machine learning algorithms such as Random Forest and Support Vector Machines (SVM), which have demonstrated superior accuracy in previous land cover studies. The classification process is conducted using the Google Earth Engine (GEE) platform, leveraging cloud computing for efficient processing of large-scale datasets [11].

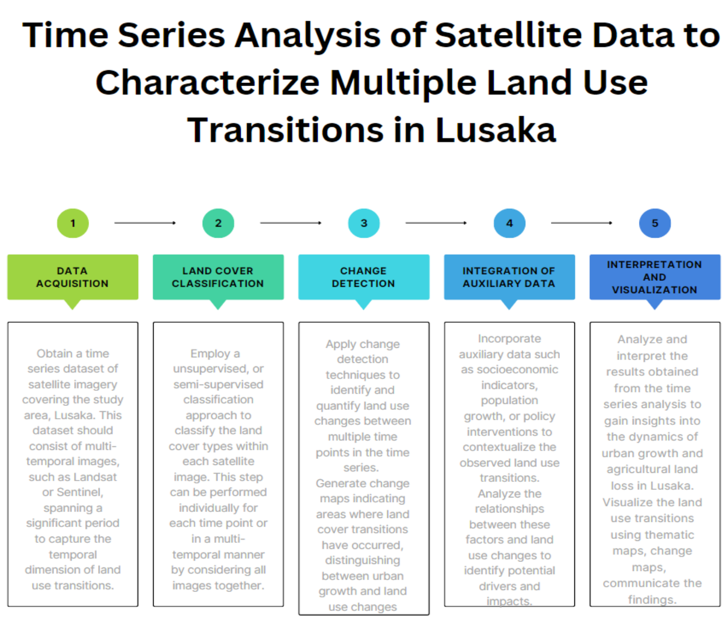


Figure 2. An outline of Time Series analysis.

A semi-automatic classification approach is utilized, allowing for precise identification of land cover types based on spectral signatures. This involves training the classification model with known land cover samples and applying it to classify the entire study area. The classification scheme includes urbanized areas, small villages, airports, marble quarries, various farmland categories, savanna, and forest/woodland [12].

Figure 3 illustrates a hybrid approach that combined pixel-based and object-based classification techniques were employed to extract the built-up area of Lusaka city. The Landsat imagery underwent pixel-based image classification, where each pixel was assigned to a specific class. Object-Based Image Analysis (OBIA) is an approach that initially segments the image into coherent objects and then classifies these objects based on their spectral, spatial, and contextual attributes. This technique considers the interconnections between neighboring pixels to enhance classification accuracy.

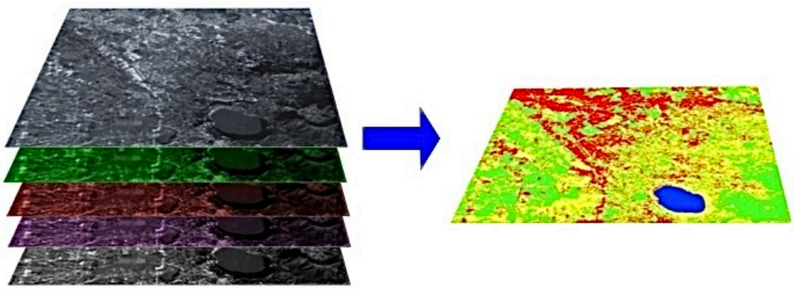


Figure 3. A multispectral image processed to produce a land cover classification. Source: [12].

4.1.1. Land Use and Land Cover (LULC) Classification and Extraction of Built-Up Area

To conduct time series analysis effectively, accurately extracting urban areas is crucial for understanding land use changes over time. This study adopts an improved classification scheme that categorizes land cover into five primary classes: urban areas, agricultural land, forest/shrubland, bare land, and water bodies. By employing a hybrid classification approach that integrates pixel-based and object-based techniques, the study enhances the precision of mapping built-up areas, reducing misclassification errors associated with spectral similarities among land cover types. The integration of the Random Forest classifier with Object-Based Image Analysis (OBIA) significantly improves classification accuracy by incorporating spatial context, texture, and spectral properties of urban features. Unlike traditional pixel-based methods, which often struggle with mixed pixels in heterogeneous urban environments, OBIA effectively segments images into meaningful objects, enhancing feature distinction. Additionally, the use of Sentinel-2 imagery, with its higher spatial and spectral resolution, facilitates better differentiation of fragmented land use types, capturing finer details of urban sprawl and informal settlements.

This methodology provides a more detailed and reliable representation of urban growth dynamics in Lusaka, enabling policymakers and urban planners to make data-driven decisions for sustainable land management. The improved classification accuracy ensures that land use transitions are effectively monitored and analyzed over time [13].

4.1.2. Unsupervised Pixel-Based Image Classification

Using the Landsat imagery of the study area, unsupervised pixel-based classification was adopted. In the unsupervised classification process, the initial step entails grouping pixels into "clusters" based on their properties using algorithms such as K-means or ISODATA. Following the selection of a clustering algorithm, the next stage involves determining the desired number of classes to be created and manually assigning each cluster with a corresponding land cover type. In this study the K-means algorithm was used (See **Figures 4-6** below).

4.1.3. Post Classification

Post-classification analysis is an essential step in the time series analysis of Landsat data for characterizing various land use changes. It involves the examination and interpretation of classified LUC maps produced from Landsat imagery at different time points. Validation of the four Landsat data was done to ascertain the correctness of land cover categorization by comparing the classified land cover maps with reference data. Reference data was collected via aerial photography, existing 1985 topographical map. It typically involves visually identifying and recording the true land cover types on the ground or through high-resolution imagery within the city of Lusaka.

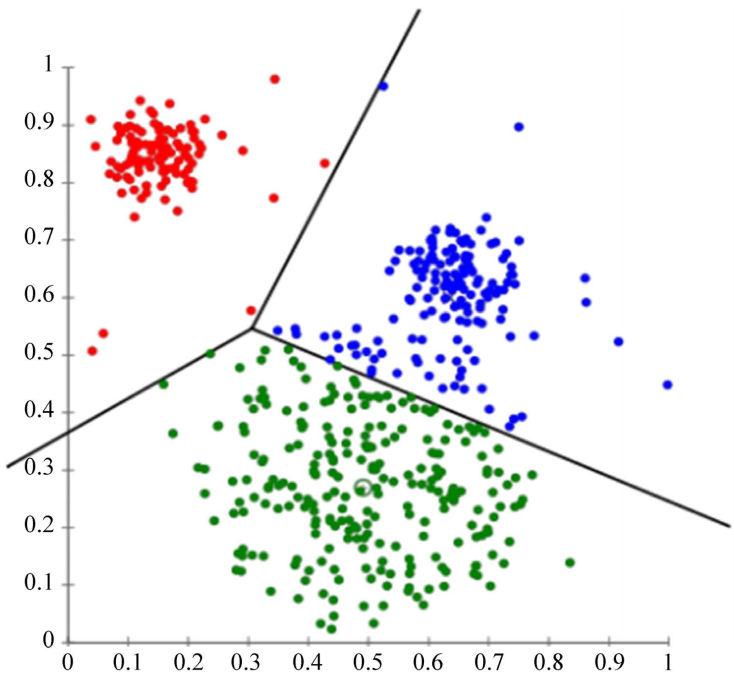


Figure 4. K means data clustering. Source: [12].

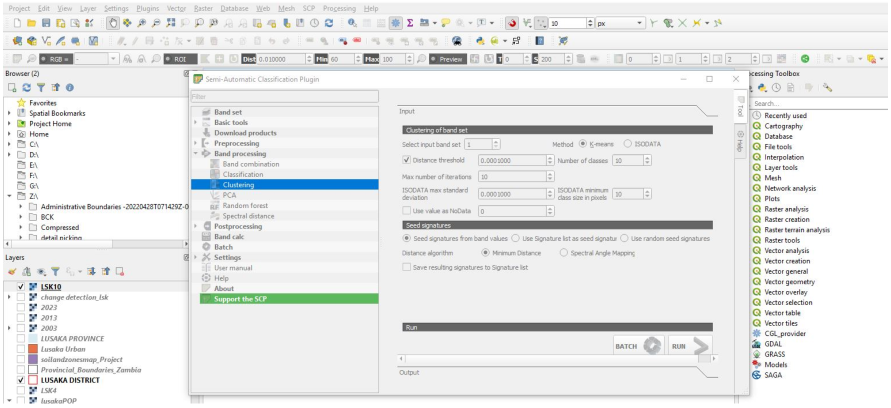


Figure 5. Operation of unsupervised classification.

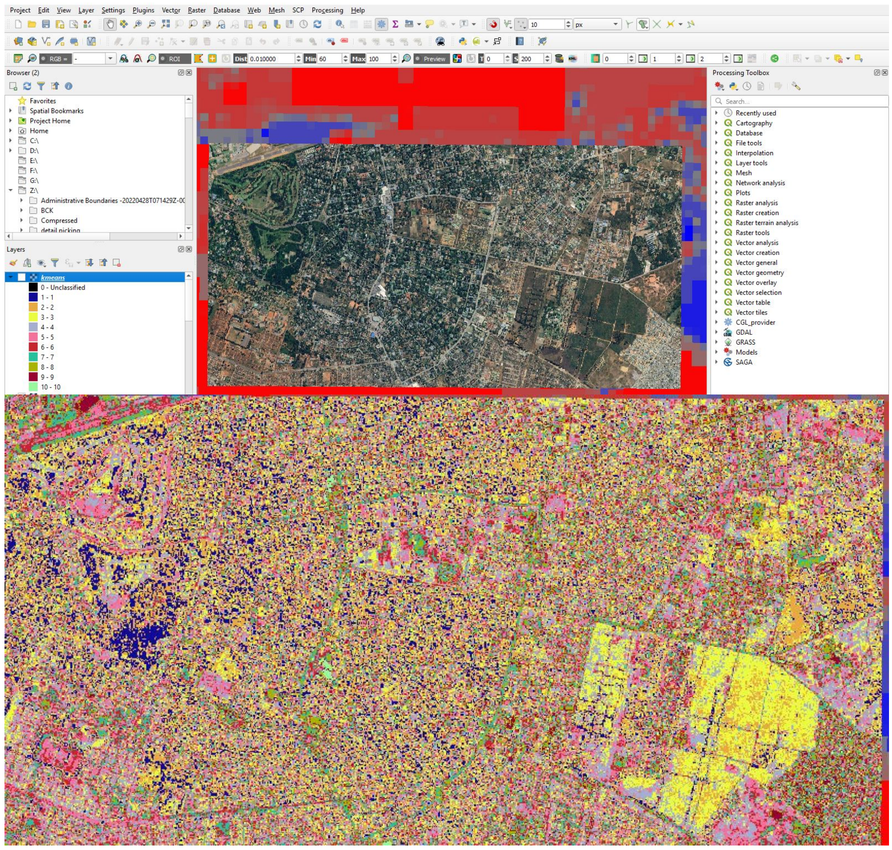


Figure 6. Result of unsupervised classification (bottom), and true colour aerial photograph (top) of the study area.

Through the comparison of classified land cover maps with reference data, the validation aids in evaluating the classification algorithm's performance and identifying any potential errors or uncertainties in the classification results [14] [15].

Post-classification analysis is crucial for evaluating land use transitions over time. Change detection techniques, including image differencing and post-classification comparison, are applied to assess urban expansion and agricultural land loss. The accuracy of classified maps is validated using ground truth data, high-resolution aerial imagery, and historical maps.

4.2. Data Interpretation and Results

Landsat imagery captured over a period from 1992 to 2024, processed with the Semi-Automatic Classification Tool in GIS, produced six (6) land cover maps. To enhance accuracy and provide a more detailed analysis, this study incorporates updated data for 2023 and 2024. The classification now utilizes high-resolution satellite imagery (10 m) to refine the spatial delineation of urban expansion and agricultural land loss [16]. A discrete classification with 23 classes, aligned with UN-FAO's land cover classification system, was applied to this study.

The time-series analysis results of Lusaka city are crucial for understanding and effectively communicating the patterns of various land-use transitions extracted from the Landsat imagery. Thematic maps illustrating the land-use changes over time provide a visual representation of the transitions occurring in Lusaka. These maps are overlaid on base maps or high-resolution imagery to provide spatial context and enhance interpretability. The study further integrates socio-economic and political analysis to explain the drivers behind urban expansion and agricultural land loss.

4.2.1. Land Use Map of Lusaka 2024

Land use map of the area of Lusaka: 1: urbanised area; 2: small villages; 3: Airport; 4: Marble quarries; 5: Medium sized farmlands; 6: Irrigated farmlands; 7: Big cultivated farmlands; 8: Small farms; 9: urbanised areas with kitchen-gardens; 10: Savanna with scattered trees; 11: Savanna; 12: Forest and woodland.

The geospatial arrangement of land use in Lusaka has undergone significant changes over the years, as depicted in **Figures 7-12**. The land use maps from 1992 to 2024 illustrate a progressive transformation, with urban expansion replacing agricultural land and natural landscapes. In 1992, the region had a balanced distribution of urbanized areas, small villages, farmlands, and natural vegetation. However, by 1999, urbanization had begun to encroach upon agricultural zones, with noticeable increases in built-up areas. By 2009, the city had experienced further densification, particularly around major transport routes and commercial centers. The 2019 land use arrangement shows accelerated urban growth, with large portions of medium-sized and irrigated farmlands being converted into urban developments. This pattern continued into 2023 and 2024, where the city's expansion significantly impacted the surrounding environment, leading to the fragmentation of farmlands and a reduction in forested areas [17].

The land use classification includes urbanized zones, small villages, airports, and various forms of agricultural land. Additionally, savanna landscapes, forested areas, and marble quarries are present within the region. The changes in land use highlight the need for sustainable urban planning to balance development with environmental conservation in Lusaka's rapidly growing metropolitan area.

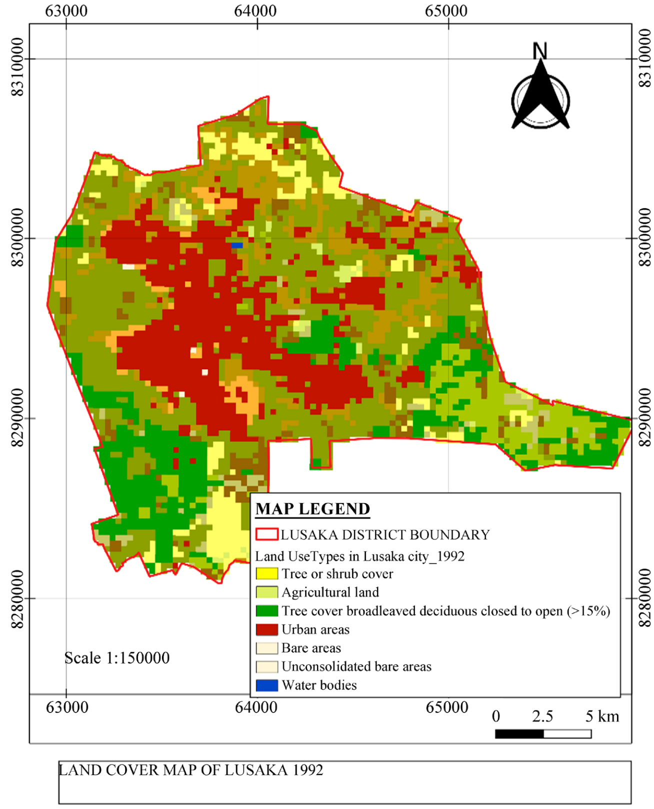


Figure 7. Geospatial arrangement of land use 1992.

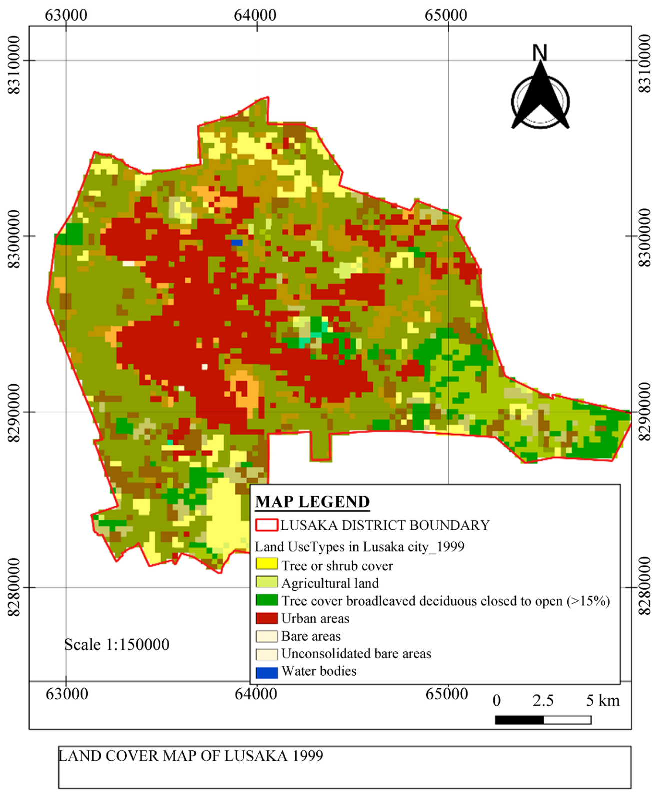


Figure 8. Geospatial arrangement of land use 1999.

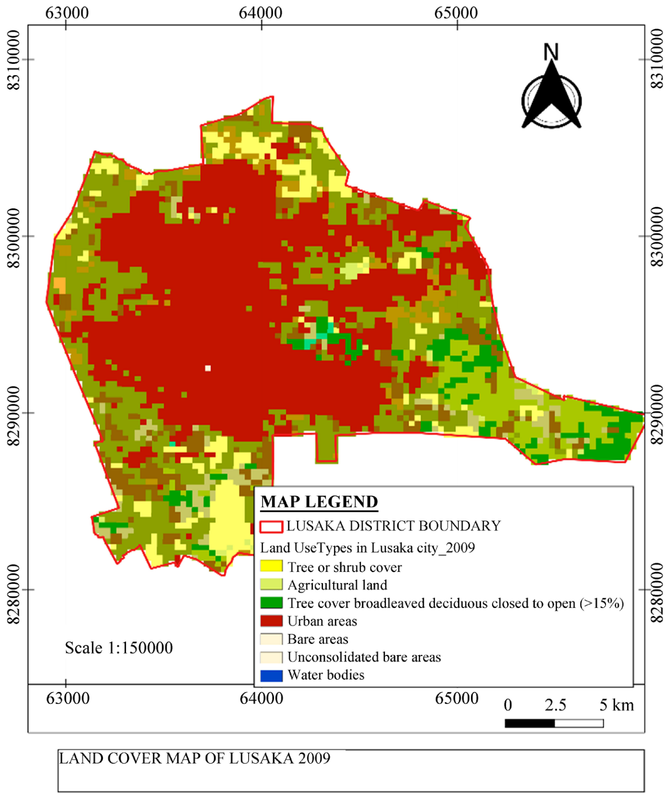


Figure 9. Geospatial arrangement of land use 2009.

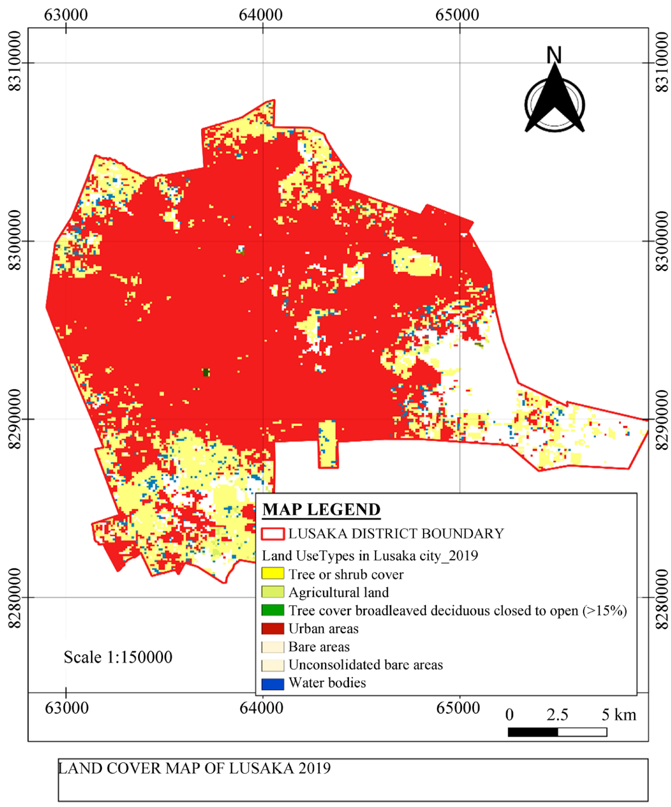


Figure 10. Geospatial arrangement of land use 2019.

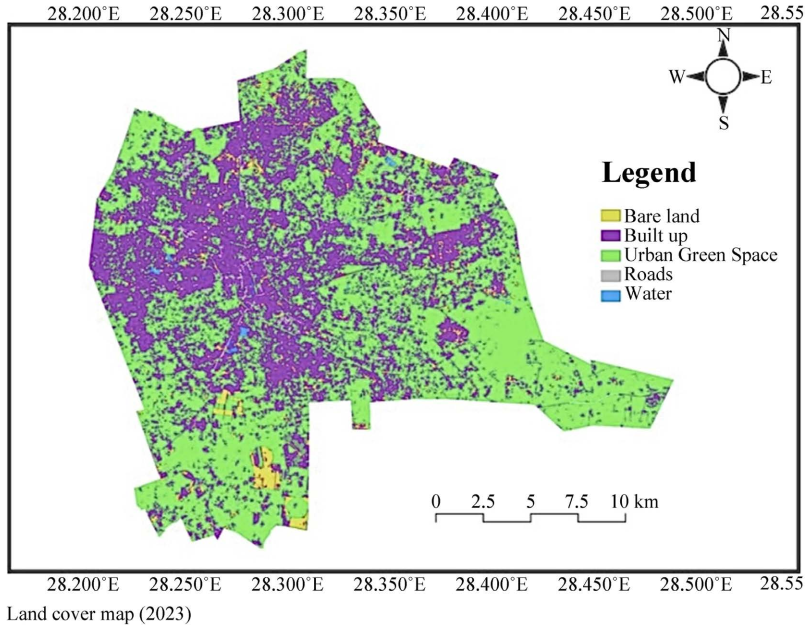


Figure 11. Geospatial arrangement of land use 2023.

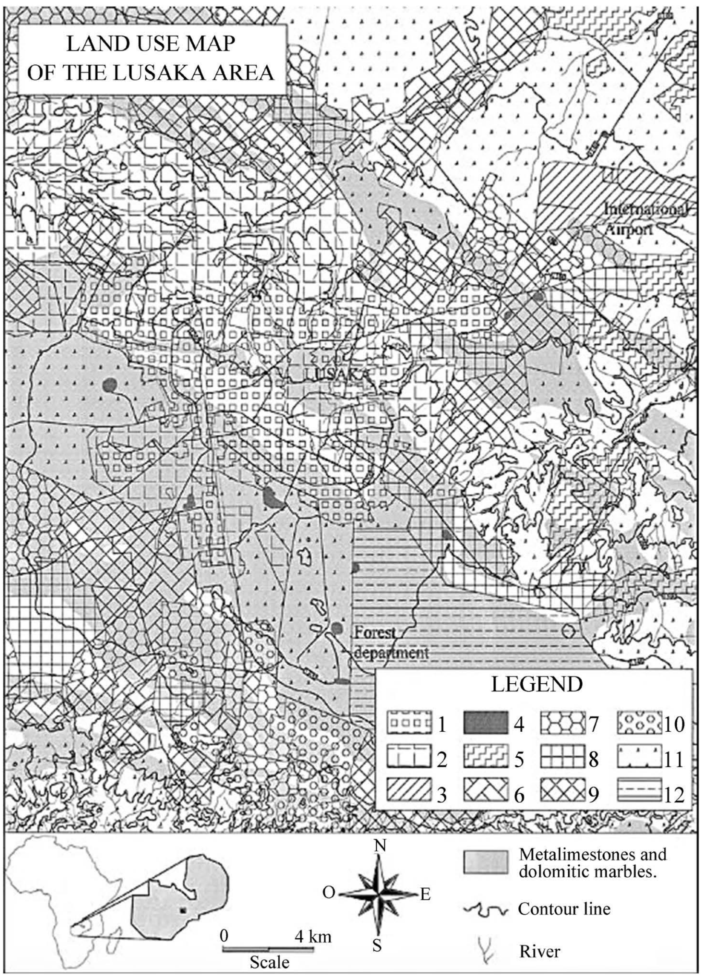


Figure 12. Geospatial arrangement of land use 2019.

4.2.2. Change Detection

The updated change detection analysis (1992-2024) reveals significant land use transitions, providing insights into the patterns of urban growth and the loss of agricultural land and forest landscapes within Lusaka's periphery. The results now include an analysis of socio-economic and political factors driving these changes, which were previously underexplored. The key findings from the change detection results are as follows:

1) Urban Growth

- The change detection analysis reveals substantial urban expansion in Lusaka over time. Built-up areas have expanded into previously undeveloped or agricultural land, with a notable increase between 2019 and 2024.
- The urban growth is characterized by the emergence of new urban clusters, the densification of existing urban areas, and the transformation of peri-urban regions into fully urbanized zones.
- High rates of urban growth are observed in specific corridors such as the Great North Road and along key transport routes, indicating the impact of economic policies and real estate development projects.

2) Agricultural Land Loss

- Agricultural land loss is evident, reflecting the conversion of agricultural zones into urbanized areas.
- The most affected areas are in the outskirts of Lusaka and the neighboring districts of Chibombo, Kafue, and Chongwe, where rapid land conversion has disrupted agricultural activities.
- The fragmentation of large farms into smaller plots has increased, affecting agricultural productivity.
- Socio-economic factors such as population growth, land tenure policies, and government housing initiatives have contributed to this land conversion.

3) Spatial Patterns and Distribution

- The spatial distribution of land-use changes shows a complex pattern of urban sprawl, particularly along key economic corridors.
- Thematic maps highlight the spatial extent of landscape transformations, identifying both stable and dynamic land cover zones.
- The study also considers the role of informal settlements in urban expansion, which has been a growing trend since 2010.

4) Temporal Trends

- The analysis identifies three key periods of accelerated change: 2000-2009, 2010-2019, and 2020-2024.
- The post-2019 period shows the highest rate of urban expansion, likely driven by infrastructure development projects and economic policies promoting real estate investments.
- Agricultural land loss peaked between 2019 and 2024, correlating with population growth and increased demand for residential and commercial land.

5) Improved Land Cover Classification Accuracy

- Previous analyses relied on a 300 m resolution, which was too coarse for detailed land-use assessments. This study improves accuracy by using high-resolution satellite imagery (10 m) to capture finer spatial details.
- The use of machine-learning algorithms in GIS classification enhanced the precision of land cover differentiation.

Figure 13: Change detection for the period 1992-2024 Visual representation of land use transitions, highlighting urban expansion and agricultural land loss.

Figure 14: Thematic composite map representing land cover changes in Lusaka over the entire time series. Thematic maps use colors, patterns, or symbols to represent different land cover categories, allowing for clear differentiation and spatial interpretation.

4.2.3. Rate of Change of Landuse

Table 1 shows the rate at which the landscape of Lusaka city changes, obtained from the time series analysis of satellite data (Landsat Imagery), provides insights into the magnitude and speed of land transitions, particularly urban growth and agricultural land loss. This study updates the dataset to include satellite imagery from 1992 to 2024, ensuring a more accurate and recent analysis of land use change. The study also incorporates socio-economic and political factors influencing these transitions and improves spatial resolution for better precision.

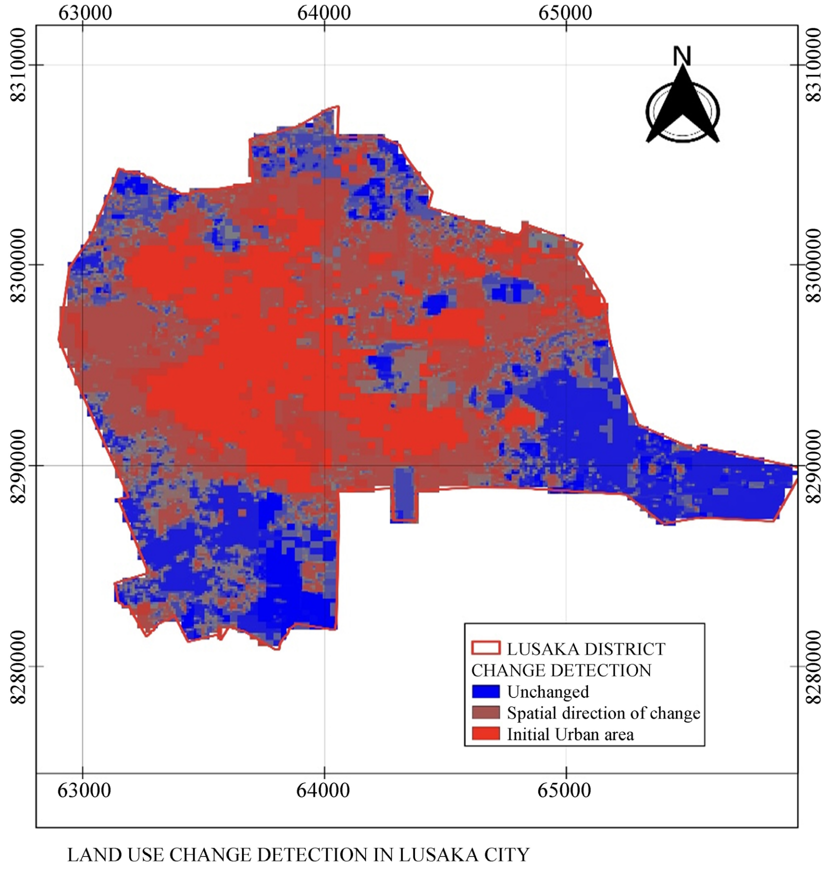
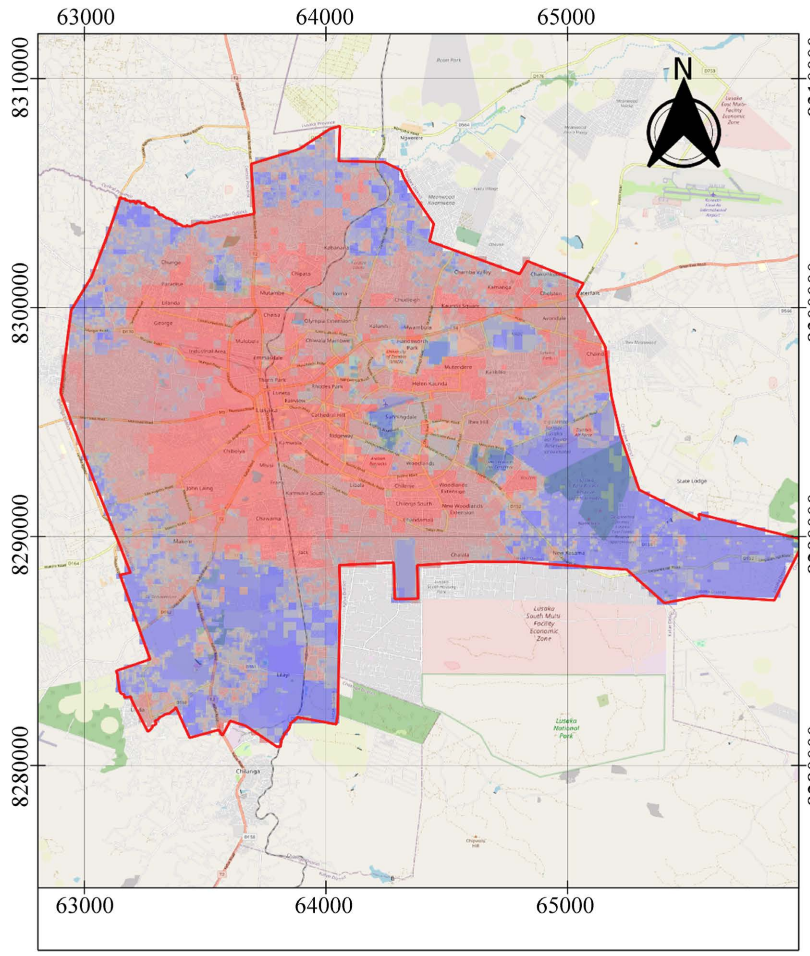


Figure 13. Change detection of for the period 1992-2024.



LAND USE CHANGE DETECTION IN LUSAKA CITY

Figure 14. Thematic map created as composite map representing land cover changes in Lusaka over the entire time series.

Table 1. Total area of land use from 1992 to 2024.

LAND USE TYPE	1992	2009	2019	2024	DESCRIPTION
Agricultural Land	166.56	155.91	120.24	102.35	Crop fields, plantations, including bare lands
Forest Area (Tree Cover)	204.77	177.2	138.23	115.67	Forest lands, trees (deciduous)
Built-Up Area	45.9	80.4	155.8	187.88	Residential, industrial, roads, urban and rural land, commercial
Water Body	1.54	1.02	0.39	0.29	Rivers, open water, reservoirs, ponds, and wetlands
TOTAL	**418.77**	**418.77**	**418.77**	**418.77**	

The study area, covering approximately 418.77 square kilometers, was analyzed using a higher spatial resolution than the previous 300-meter resolution. The land use classification unveiled a complex amalgamation of urban land uses (ULU) throughout the area, while the outskirts were predominantly characterized by bare agricultural lands. Geographic Information Systems (GIS) was used to calculate the area (in square meters) of the different land use classifications. The recommended technique was to use the unique raster layer values, *i.e.*, pixel count of the Landsat data, and multiply it by the area of each pixel for the different classes identified.

Urban Growth Rate

analysis reveals a rapid rate of urban growth in Lusaka over the study period. The city's expansion and the conversion of non-urban land cover classes into urban areas demonstrate the intensity of urbanization. The rate of urban growth varies across different regions or neighborhoods within Lusaka, with hotspots of development exhibiting a higher rate of change compared to other areas. The rate of change of urban growth is expressed using the formula:

$$Rate\ of\ Change\ of\ Urban\ Growth = \frac{Urban\ Area\ at\ Time\ t_2 - Urban\ Area\ at\ Time\ t_1}{t_2 - t_1}$$

where:

Built-Up Area at Time t_2 is the extent of the built-up area in 2024.

Built-Up Area at Time t_1 is the extent of the built-up area in 1992.

$(t_2 - t_1)$ represents the time interval between the two time points *i.e.*, 32 years.

With the updated area computed, the urban growth rate of Lusaka is now at 4.44% per year, reflecting an acceleration in urban expansion over the last five years.

4.2.4. Findings on Socio-Economic and Political Factors Influencing Urban Expansion and Agricultural Land Loss

Lusaka's rapid urban expansion and the subsequent decline of agricultural land are influenced by various socio-economic and political factors. One of the key drivers of this transformation is population growth. Lusaka has experienced significant population increases due to rural-to-urban migration and natural population growth. The rising number of people seeking employment, housing, and social amenities has led to an increased demand for land, causing urban expansion into previously agricultural areas. As the population grows, land previously used for farming is being converted into residential, commercial, and industrial developments to accommodate the expanding urban population.

Another major contributing factor is economic development. The expansion of industries, business hubs, and commercial centers has accelerated the conversion of agricultural land into urban settlements. The increase in investments, particularly in real estate and manufacturing, has further driven the demand for land, leading to a transformation of the urban landscape. The rise of Lusaka as an economic center has attracted investors, further intensifying land-use competition and contributing to agricultural land loss. Large-scale infrastructure projects, such as road expansions, shopping malls, and industrial parks, have also played a significant role in this transition.

Policy and governance have also played a crucial role in urban expansion.

Government policies that promote urbanization, encourage real estate investment, and support large-scale infrastructure projects have contributed to the rapid expansion of urban areas. Some of these policies aim to attract foreign and local investors, leading to significant construction activities. However, weak enforcement of land-use regulations and ineffective zoning policies have contributed to unplanned urban growth, which often encroaches on productive agricultural land. The lack of strict urban planning measures has allowed urban sprawl to expand unchecked, resulting in significant land-use changes over the years.

Changes in land tenure systems have also contributed to urban expansion and agricultural land loss. The shift from customary land tenure systems to formal land ownership has facilitated land commercialization. As land becomes a valuable economic asset, individuals and investors are more inclined to sell or repurpose agricultural land for urban developments. Additionally, informal land markets have played a significant role in unplanned urban expansion, with land transactions occurring outside formal regulatory frameworks. This has led to the proliferation of informal settlements and urban sprawl, further encroaching on agricultural lands.

Environmental and climate factors have further influenced land-use transitions in Lusaka. Climate change has had significant impacts on agricultural productivity, making some farming areas unsuitable for cultivation. As agricultural yields decline due to erratic rainfall patterns, soil degradation, and drought, farmers often sell their land to developers. In addition, natural disasters such as floods have made some agricultural zones less viable, increasing their susceptibility to conversion into urban areas. These environmental changes have contributed to a shift away from agricultural land use and toward urban expansion.

4.2.5. Implications for Policy and Urban Planning

The findings of this study have significant implications for urban development planning in Lusaka. The increasing rate of urbanization necessitates the implementation of sustainable urban growth strategies that minimize the impact on agricultural land. Policymakers and urban planners need to adopt a balanced approach that accommodates urban expansion while ensuring that agricultural land remains protected for food security and environmental sustainability. Developing zoning regulations that prevent uncontrolled land conversion and promoting vertical expansion rather than horizontal sprawl can help mitigate agricultural land loss.

Agricultural land preservation should also be prioritized in policy discussions. Unchecked urban expansion poses a threat to food security, as productive farmland is continuously lost. To address this issue, policies should be put in place to designate and protect specific areas for agricultural use, preventing further encroachment by urban developments. Incentives such as tax benefits for maintaining agricultural land and promoting sustainable farming practices within urban settings can also help strike a balance between urbanization and food production.

Sustainable land use practices should be encouraged to ensure that urbanization does not come at the expense of environmental sustainability. Mixed land-use planning can integrate agricultural spaces within urban developments, allowing for urban farming and green spaces that support both ecological and economic goals. This approach can promote more sustainable urban expansion while reducing the negative impacts of land-use changes on biodiversity and local ecosystems.

Strategic infrastructure development is also essential for managing urban growth effectively. As Lusaka continues to expand, urban planners must ensure that infrastructure projects such as roads, water supply systems, and public services are well-planned to support the growing population. A well-designed urban infrastructure system can help prevent haphazard urban sprawl and facilitate a more organized and sustainable expansion of the city.

Finally, future projections and scenario modeling based on the updated data can help policymakers anticipate trends and make informed decisions. By analyzing the rate of land-use change, urban planners can develop predictive models that estimate how urban expansion will unfold in the coming years. This information is crucial for long-term urban planning, as it allows decision-makers to implement proactive measures to mitigate potential negative impacts. Future research should focus on assessing different urban growth scenarios and evaluating their implications for land use, economic development, and environmental sustainability.

5. Discussion Findings

This section analyzes key findings on land use classification accuracy, urban expansion, agricultural land loss, and socio-economic drivers. It evaluates classification methods, urban growth trends, environmental impacts, and policy influences. The discussion highlights implications for urban planning and sustainability, offering recommendations to balance development with environmental conservation.

5.1. Land Use and Land Cover Classification Accuracy

The findings from the study indicate that the supervised classification approach using machine learning algorithms such as Random Forest and Support Vector Machines (SVM) yielded high classification accuracy. The integration of Object-Based Image Analysis (OBIA) significantly improved the precision of land cover mapping by incorporating spatial, spectral, and contextual properties. The combination of Sentinel-2 and Landsat imagery enabled the study to capture fine-scale land use changes, particularly in fragmented urban and peri-urban environments. Unsupervised classification using the K-means algorithm provided additional insights, especially in identifying land cover transitions without prior knowledge of training samples. The clustering of spectral signatures allowed for an independent assessment of land cover classes, enhancing the robustness of the classification. However, misclassification of spectrally similar features such as built-up areas and barren land was observed in some cases, necessitating post-classification corrections.

5.2. Urban Expansion Trends

The time-series analysis from 1992 to 2024 reveals a clear trend of rapid urban expansion in Lusaka, with built-up areas increasing substantially over the study period. In 1992, urban development was largely concentrated in the central business district (CBD) and immediate surrounding areas. However, by 1999, expansion had begun extending along major transport corridors, particularly along the Great North Road. By 2009, urban densification had become more pronounced, with peri-urban areas transforming into fully urbanized regions. The highest rates of urban growth were observed between 2019 and 2024, where informal settlements and commercial developments rapidly replaced agricultural and vacant land. Key urban expansion hotspots included areas along the Lusaka-Chongwe and Lusaka-Kafue corridors.

5.3. Agricultural Land Loss and Environmental Impacts

The study reveals that agricultural land has been significantly impacted by urban expansion, with a steady decline in farmland over the years. In 1992, agricultural zones occupied a substantial portion of the study area, with medium-sized and irrigated farmlands dominating the outskirts of Lusaka. However, by 1999, urban encroachment had begun affecting these agricultural areas, particularly in Chibombo, Kafue, and Chongwe districts. The rate of agricultural land loss accelerated from 2009 onwards, with farmland being fragmented and converted into residential, commercial, and industrial developments. This trend poses significant challenges for food security and sustainable land management, as productive farmland continues to be lost to urbanization.

Additionally, the conversion of green spaces, such as savanna and forested areas, has contributed to environmental degradation. Deforestation and loss of natural vegetation have been observed in several locations, particularly where urban expansion has been most intense. This has implications for biodiversity conservation and climate resilience, as green cover plays a crucial role in maintaining ecological balance.

5.4. Change Detection Analysis and Socio-Economic Drivers

The change detection analysis conducted between 1992 and 2024 provides crucial insights into the factors driving land use transitions in Lusaka. The study highlights several socio-economic and political influences that have shaped urban expansion and contributed to the loss of agricultural land. Understanding these drivers is essential for formulating effective urban planning and land management strategies.

One of the primary drivers of land use change is population growth. The rapid increase in Lusaka's population has significantly contributed to the expansion of built-up areas. As more people migrate to the city in search of better employment opportunities and improved living conditions, the demand for housing, infrastructure, and commercial spaces has risen. This demand has led to the conversion of agricultural and undeveloped land into residential, commercial, and industrial zones, exacerbating land scarcity and urban sprawl. Another key factor is economic policies that have influenced urban development. Government-backed real estate projects, infrastructure investments, and incentives for commercial development have accelerated land conversion. Policies encouraging industrialization and private sector investment have spurred construction activities, often at the expense of green spaces and agricultural land. Additionally, economic reforms aimed at boosting urban economic activities have indirectly fueled land transformation, particularly in areas with high commercial potential.

Rural-urban migration has further intensified land use changes in Lusaka. The movement of people from rural areas to urban centers in search of employment and better services has increased informal settlements. This migration has led to unplanned urban expansion, with many peri-urban areas experiencing rapid and uncontrolled development. The rise of informal housing has resulted in land fragmentation and inefficient land use patterns, creating challenges for infrastructure provision and environmental management. Land tenure and policy reforms have also played a crucial role in shaping land use patterns. Weak land tenure systems and inconsistent land-use policies have facilitated the uncontrolled conversion of agricultural land into urban plots. The absence of strict zoning regulations and enforcement has allowed for speculative land buying and uncoordinated urban expansion. Without clear land ownership structures, land disputes and irregular land allocations have become common, further complicating efforts to implement sustainable land management strategies.

Overall, the socio-economic and political factors driving land use transitions in Lusaka highlight the need for integrated planning approaches. Addressing these challenges requires coordinated efforts in policy formulation, land governance, and infrastructure development to ensure sustainable urban growth while preserving critical agricultural and ecological resources.

5.5. Implications for Urban Planning and Sustainable Development

The rapid expansion of Lusaka presents significant challenges for sustainable land management, necessitating proactive urban planning measures. The findings emphasize the urgent need for strategic interventions to balance urban growth with environmental and socio-economic sustainability. Without effective planning, the city risks continued loss of agricultural land, increased congestion, and environmental degradation. To address these challenges, the study recommends several key strategies aimed at promoting sustainable urban development.

One of the most crucial recommendations is the implementation of smart growth strategies. By encouraging compact urban development and mixed land-use planning, policymakers can optimize land utilization while minimizing urban sprawl. High-density, well-planned residential and commercial developments can help reduce the pressure on peri-urban agricultural lands and prevent unregulated settlement expansion. Additionally, integrating public transportation systems into urban planning can enhance mobility, reduce traffic congestion, and promote efficient land use. Another essential measure is the preservation of agricultural land. With urban expansion threatening food security, it is critical to establish zoning regulations that protect productive farmland. Designating specific areas for urban agriculture can help maintain food production within city limits and support livelihoods. Furthermore, encouraging vertical farming and other innovative agricultural practices in urban areas can contribute to sustainable food systems and reduce dependence on external food supplies.

Strengthening land governance is also necessary to ensure orderly urban expansion. Weak land tenure policies have facilitated uncontrolled land conversion, often leading to land disputes and inefficient land use patterns. Enforcing strict land-use regulations and improving transparency in land allocation can prevent speculative land purchases and unauthorized developments. Equitable land distribution policies can also enhance access to affordable housing while reducing informal settlements and unplanned urban growth. Lastly, environmental conservation initiatives are vital in mitigating the ecological impact of urbanization. Afforestation programs, green infrastructure projects, and sustainable drainage systems can help preserve green spaces and reduce environmental degradation. Incorporating eco-friendly building practices and promoting renewable energy solutions in urban development can further enhance environmental resilience.

Effective urban planning and sustainable development strategies are essential for managing Lusaka's growth. By integrating smart planning, land conservation, governance reforms, and environmental initiatives, the city can achieve a balanced approach to urbanization while safeguarding natural and agricultural resources for future generations.

5.6. Conclusions

The findings of this study provide compelling evidence of the profound impact of urbanization on Lusaka's land use patterns over the past three decades. The analysis underscores the effectiveness of supervised classification approaches such as Random Forest and Support Vector Machines in achieving high classification accuracy, particularly when integrated with Object-Based Image Analysis. The use of both Sentinel-2 and Landsat imagery allowed for precise detection of land use changes, though challenges related to spectral similarities among certain land cover classes required post-classification refinements. Additionally, unsupervised classification methods like the K-means algorithm contributed to independent land cover assessments, enhancing the robustness of the classification process.

Urban expansion has been the most dominant land use change, with built-up areas increasing substantially from 1992 to 2024. The most rapid periods of growth occurred between 2019 and 2024, particularly along major transport corridors such as the Lusaka-Chongwe and Lusaka-Kafue routes. This expansion has come at a cost, with significant losses of agricultural land, particularly in peri-urban areas such as Chibombo, Kafue, and Chongwe districts. The encroachment on farmlands raises concerns about food security and sustainable land management, as the conversion of agricultural zones into residential and commercial developments continues unchecked. Furthermore, the environmental consequences of urbanization have been considerable. The loss of green spaces, deforestation, and the degradation of natural vegetation threaten biodiversity conservation and climate resilience. The removal of tree cover and natural habitats disrupts ecological balance, leading to increased carbon emissions and reduced climate adaptation capacity. These environmental concerns necessitate proactive conservation efforts and the integration of green infrastructure in urban planning.

The study identifies several socio-economic drivers influencing these changes, including rapid population growth, economic policies promoting real estate development, rural-urban migration, and weak land governance frameworks. The lack of effective land tenure policies has facilitated unregulated land conversion, contributing to informal settlements and inefficient land use practices. Without strategic interventions, Lusaka's urban growth trajectory may exacerbate socio-economic inequalities and environmental vulnerabilities.

To address these challenges, the study highlights the need for strategic urban planning that prioritizes sustainable development. Key recommendations include implementing smart growth strategies to reduce urban sprawl, enforcing zoning regulations to protect agricultural land, strengthening land governance mechanisms, and promoting environmental conservation initiatives such as afforestation and green infrastructure projects. By adopting these measures, policymakers and urban planners can balance the demands of economic development with environmental preservation, ensuring the long-term resilience of Lusaka's metropolitan area. The insights from this study serve as a crucial foundation for future research and policy formulation aimed at fostering sustainable urban growth and land management.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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List of Acronyms

GIS: Geographical Information System
RS: Remote Sensing
ULU: Urban Land Use
LULC: Land use/land cover
LUC: Land Use Change