

**BUSITEMA  
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**SPATIOTEMPORAL IMPACT OF URBAN EXPANSION ON CARBON SEQUESTRATION  
IN JINJA CITY**

**BY**

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**A dissertation submitted to the Directorate of Graduate Studies, Research And Innovation  
in partial fulfillment for the award of Master of Science in Climate Change and Disaster  
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**DATE    OCTOBER 2025**

Declaration

I sincerely certify that the work in this proposal, titled "Spatial-Temporal Impact of Urban Expansion on Carbon Sequestration in Jinja City," is my original creation and has not been submitted for any award at any higher education institution. The project was carried out under the guidance of Prof. Moses Isabirye and Dr. Saul Daniel Ddumba, my supervisors.

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Approval

This study, titled “ Spatial-Temporal Impact of Urban Expansion on Carbon Sequestration in Jinja City” was conducted by ANTONY KADUUMA as part of the requirements for his Master’s degree at Busitema University. It has been reviewed and approved, confirming that it meets the necessary academic and ethical standards for scholarly research.

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## Dedication

I dedicate this research to my family, especially my wife, Dr. Nakimuli Florence, whose unwavering support and encouragement have been my greatest strength, and to my mentors and colleagues, whose guidance and insights have shaped my academic journey. Special appreciation goes to the people of Jinja City, whose evolving urban landscape inspired this study. May this work contribute to a deeper understanding of urban expansion and its impacts, fostering sustainable development and environmental conservation for future generations.

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## Abbreviations /Acronyms

AGB Above-ground Biomass

AR6 sixth assessment report

CASA Carnegie-Ames-Stanford Approach

GHG Green House Gas

IPCC international panel on climate change

NPP Net Primary Productivity

UNFCCC United Nations Framework Convention on Climate Change

LG local government

ULI urban land index

UEI urban expansion index

UNCCD United Nations Convention to Combat Desertification

UG Government of Uganda

## Abstract

Uganda's rapid urbanization at 5.2% annually includes Jinja's quick growth, with 3% population increase driven by various factors. Despite concerns about encroachment, Jinja's green infrastructure remains vital for climate mitigation because it absorbs CO<sub>2</sub>, though growth hampers sequestration. This study analyzed how urban expansion affects Jinja's carbon sequestration to support SDGs 11 and 13 using a spatial–temporal quantitative research design, GIS analysis of 2001, 2011, and 2021 remotely sensed satellite data, with the CASA model and indices like the Urban Expansion Index and urban land index.

This study analyzes the relationship between urban expansion and carbon changes from 2001 to 2021 using Landsat data. The study calculated NPP, carbon stocks, sequestration, and calculated urban expansion metrics like ULI and UEI. Results show rapid development: Jinja's built-up area nearly doubled, with ULI rising from 6.54% in 2001 to 9.85% in 2021, and UEI from 0.142% (2001–2011) to 0.188% (2011–2021). Jinja experienced significant outward growth from 2001 to 2011, driven by unregulated urban sprawl into high-carbon green spaces, resulting in a substantial loss of carbon stocks, consistent with the UNCCD PRAIS4 Uganda report. Northern Division (which includes Mafubira, Bugembe, and Budondo) has become the main growth area, whereas the Southern Division (the old municipality) experienced slower spatial expansion. spatial regression analysis reveals, from 2001 to 2011, the urban expansion coefficient was statistically significant and negative ( $-23,760$ ;  $p = 0.001$ )

Quantifying both urban expansion and carbon sequestration from past trends enhances understanding of climate dynamics and supports sustainable urban planning for future urban growth, emphasizing the development of green cities.

## CHAPTER ONE GENERAL INTRODUCTION

### 1.1 Background of the study

Although urban areas occupy a tiny proportion of the Earth's surface, their presence and expansion significantly drive several global environmental processes, including the carbon cycle. They also account for about 50% of the Earth's population and contribute approximately 75% of the world's greenhouse gases. It's also evident that existing urban centers are rapidly expanding and new ones are getting established. As a result, the Urban areas in Africa are losing tree and vegetation cover slowly(Rui Yao et al., 2019). Urban green spaces that formerly occupied recreational grounds, swamps, and urban forests are being replaced by housing, industry, and other urban infrastructure(Hedrick-Wong et al., 2011). Rapid urbanization, characterized by rapid population growth, high levels of poverty, reduced advancement in technology, and weak institutions in Africa, jeopardizes urban green space that is likely to be even more severe if not controlled(Hedrick-Wong et al., 2011).

Nationally, Uganda's urbanization rate is approximately 5.2% per year, making it one of the highest in Sub-Saharan Africa (National Planning Authority, 2020). Guided by Uganda Vision 2040 and the Third National Development Plan. Uganda Vision 2040 aims to transform Uganda from a mainly peasant, low-income country to a competitive upper-middle-income country. It plans to do this by creating regional and strategic cities as key drivers of the country's development agenda (National Planning Authority, 2022). To reach this goal, the Ugandan government approved the creation of 15 new cities, including Jinja. This move was made to promote urbanization and industrialization. This likely explains the focus on Jinja City. Factors such as population increase, rural-to-urban migration, and economic development projects are responsible for the expansion.

Jinja City has undergone rapid urban growth over the past twenty years, transforming from a small industrial town into a sprawling urban area extending toward its peri-urban neighborhoods like Budondo, Mafubira, and Bugembe. This expansion, fueled by population growth, industrialization, and infrastructure development along the Kampala–Jinja corridor, has led to notable land-use changes. The Jinja-Kampala-Mpigi (JKM) Corridor, which includes Jinja, accounts for about 15% of the national population and over 30% of Uganda's GDP.

Research has shown that urban expansion diminishes overall vegetation biomass and disrupts ecological networks, thereby reducing carbon sequestration efficiency (Churkina, 2016; Simkin et al., 2022). Environmental degradation which is a common phenomena in many African urban centres creates pressure on fragile ecosystems such as wetlands and forests which are potential carbon sinks and play an important role in carbon sequestration. The urban trees and vegetation experience reasonable risk and vulnerability based on the fact that they are located in regions of rapid population and industrial growth. Urban vegetation plays a key role in sequestering urban carbon through the absorption and storage of urban carbon dioxide and also reduces automobile pollution.

Urban planting can achieve net savings of carbon emissions of up to 18 kg CO<sub>2</sub> per year for each tree, depending on the species. This benefit is equivalent to what 3 to 5 forest trees of comparable size and health can provide (Hedrick Wong et al., 2011). Tree canopies contribute to cooling the microclimate by shading the ground directly and promoting transpiration indirectly. Additionally, trees offer significant emotional and aesthetic value to residents and are vital to urban ecosystems as part of green infrastructure. Commonly used metrics for studying carbon sequestration in forests include Net Primary Productivity (NPP) and Above-Ground Biomass (AGB). NPP is defined as the net carbon gain by plants in natural ecosystems and is calculated by subtracting autotrophic respiration from the gross photosynthetic carbon uptake (Churkina, G. 2016). The NPP index serves as an indicator of carbon sequestration, ecosystem health, and agricultural yields, which are crucial for assessing climate change impacts and mitigation strategies.

AGB refers to the living vegetation, including both woody and herbaceous above the soil (Brown, S. 1997). AGB is one of the most reliable ways of measuring carbon sequestration levels which is always expressed as mass per unit area. Estimation of AGB and NPP is necessary for exploring the carbon sequestration potential of urban green space. Estimation of both indices of carbon sequestration can be done via direct and indirect methods.

Loss of vegetation not only reduces biodiversity but also diminishes ecological functions such as carbon sequestration, water regulation, and soil protection. These trends highlight the urgent need for sustainable urban planning that integrates green infrastructure conservation to balance Jinja's development trajectory with environmental resilience.

## 1.2 Statement of the problem

Jinja City, a rapidly urbanizing hub in Uganda, is experiencing significant land use transformations driven by population growth, industrialization, and infrastructure development (National Planning Authority, 2020). These transformations are evident through urban expansion that has led to the conversion of green areas into impervious surfaces, resulting in the loss of urban green spaces that are essential for carbon sequestration and climate regulation. Urban green spaces, including parks, street trees, and other vegetated areas, play a critical role in mitigating climate change by acting as carbon sinks, absorbing atmospheric carbon dioxide (CO<sub>2</sub>) through photosynthesis and storing it in biomass and soils. The reduction of these green spaces not only diminishes the city's capacity to sequester carbon but also exacerbates urban heat island effects, decreases air quality, and negatively impacts biodiversity (UN-Habitat, 2022).

Despite the recognized importance of urban vegetation in climate mitigation, there is a paucity of research quantifying the impact of urbanization on carbon sequestration dynamics in rapidly developing cities like Jinja. This knowledge gap hinders the integration of green infrastructure into urban planning, potentially leading to unsustainable development patterns that compromise environmental resilience. To address this gap, the study aims to conduct a spatial-temporal analysis of urban expansion in Jinja City over the years 2001, 2011, and 2021, assessing its drivers and quantifying its impact on carbon sequestration. This research provided empirical data to inform sustainable urban planning strategies that prioritize the preservation and enhancement of green spaces. Such insights are essential for developing climate-resilient urban environments that balance development needs with ecological sustainability.

## 1.3. Objectives of the study

The study aimed to address the following objectives

### 1.3.1 Main objective

The study's main objective was to analyse how the urban expansion of Jinja City is impacting carbon sequestration capacity in order to generate evidence to integrate green infrastructure and ecosystem conservation into urban development planning.

### 1.3.2 Specific objectives

The study addressed the following specific objectives.

1. Analyze the spatiotemporal patterns of urban expansion in Jinja City.
2. Quantify the spatiotemporal trends in carbon stocks in Jinja city.
3. To assess the relationship between urban expansion and carbon sequestration in Jinja City.

### 1.4 Research question

This study addressed the following questions.

1. How did the urban expansion pattern change from 2001 to 2021?
2. What are the trends in carbon sequestration of urban green spaces in Jinja City?
3. How does urban expansion affect carbon sequestration levels in Jinja city?

### 1.5 Conceptual framework

This study's framework illustrates the relationship between urban expansion and carbon sequestration in Jinja City, grounded in the Spatial Diffusion Theory and the Ecosystem Services Framework. Hagerstrand (1953) explains spatial diffusion as the process by which urban growth spreads from a central point over time, influencing nearby areas. As Jinja City expands driven by population growth, industrialization, and infrastructure development, vegetated areas are increasingly replaced by impervious surfaces. These spatial changes alter ecosystem structure and function, leading to a reduced capacity for the city to store and absorb atmospheric carbon, a vital regulatory service that helps maintain local and global climate stability (Millennium Ecosystem Assessment [MEA], 2005).

This framework considers urban expansion as the independent variable, assessed through indicators such as urban land index (ULI) and urban expansion index (UEI), while the carbon sequestration capacity is the dependent variable, measured by indicators like Net Primary Productivity (NPP), Above-Ground Biomass (AGB), and total carbon stock. The connection between them is influenced by land conversion and vegetation loss, which are typically indicated by declines in the Normalized Difference Vegetation Index (NDVI) and vegetation productivity (Yao et al., 2019). External factors such as climate, soil quality, and land-use policies also indirectly impact both urban growth and ecosystem carbon dynamics (Li et al., 2020; Isabirye et

al., 2016). In sum, these factors shape how urbanization affects ecological change and the resilience of landscapes that store carbon.

The framework directly highlights that unregulated urban growth reduces the regulating ecosystem services provided by urban vegetation, thereby undermining climate-mitigation potential (Seto et al., 2012; Cobbinah et al., 2019). By combining CASA mode with spatial analysis, the framework offers an evidence-based method to understand how human-driven land use changes impact carbon storage. The insights gained will guide policies promoting green infrastructure and sustainable urban planning in Jinja City, supporting Uganda's low-carbon development goals.

### 1.6 Justification of the study

Jinja city expansion and its dynamics have been hot research topics for the last 3 decades. The underlying reason is that urbanization directly impacts energy and material flow for example carbon emissions, waste generation, and infrastructural developments (Jia et al., 2019). Urban expansion also affects natural ecosystems and the quality of life of their inhabitants. As cities expand, the pressure on natural resources and agricultural land also increases which in turn creates pressure on natural resources that play vital roles in mitigating against the global environmental problem of climate change. Green spaces in urban areas absorb large amounts of carbon dioxide and act as sinks for carbon that store carbon dioxide. In the due process, urban green spaces largely play a role in mitigating climate change.

According to the Ministry of Energy, 90% of the Ugandan population is dependent on natural resources as the major source of energy for cooking and lighting. A good percentage of Ugandan families rely on biomass for energy thus creating a huge demand for trees for both charcoal and firewood. The need for energy, especially charcoal and firewood, contributes towards total CO<sub>2</sub> emissions. This creates the need to understand the contribution of biomass in carbon sequestration as a mitigation strategy for carbon dioxide which is among major greenhouse gas to address climate change at a microscale of Jinja City. Quantifying the relationship between urban growth patterns and carbon sequestration will provide insights into the trade-offs between urban development and ecosystem service preservation. The findings of this research can guide the integration of green infrastructure and urban sustainability initiatives into city planning.

### 1.7 Significance of the study

Urban expansion is one of the most urgent environmental issues facing rapidly growing secondary cities like Jinja, where unplanned growth increasingly threatens natural carbon sinks such as forests, wetlands, and urban green spaces. Despite Uganda's strong policy support for sustainable development, there remains a knowledge gap in understanding how specific spatial patterns of urbanization affect local carbon sequestration dynamics. This study addresses this gap by using geospatial and remote sensing techniques to measure the spatial and temporal relationship between urban growth and carbon storage in Jinja City from 2001 to 2021. The results provide localized, data-driven insights to help urban planners and environmental managers in Jinja balance development with ecological health. The study practically helps create urban expansion policies that incorporate carbon management, offering a framework that other fast-growing Ugandan cities can adopt. Academically, it advances understanding of urban-carbon interactions in sub-Saharan Africa, a region with limited spatially explicit carbon data. While this research aligns with the National Development Plan III, especially its goals of sustainable resource use and climate resilience, it also supports Uganda's international commitments under the Paris Agreement and the Sustainable Development Goals (SDG 11: Sustainable Cities and Communities; SDG 13: Climate Action) by providing evidence-based guidance for climate-smart urban planning and emission reductions.

### 1.8 Scope of the study

The study area is located on the northern shore of Lake Victoria and the eastern bank of the Nile River, covering approximately 767 square kilometers. This study focused on estimating carbon sequestration levels as the city undergoes urban expansion. It was conducted between November 2024 and May 2025 to analyze the years 2021, 2011, and 2001 in Jinja. The research utilized remotely sensed data obtained from the USGS website and incorporated indices such as NPP and AGB to determine carbon sequestration levels. Additionally, supervised classification was used to develop land cover classes.

## CHAPTER TWO LITERATURE REVIEW

### 2.1 Introduction to Urban Expansion and Carbon Sequestration

#### 2.1.1 Definition of urban expansion and its significance

The concept of urban expansion refers to the spatial growth of developed areas resulting from population growth, industrialization, and infrastructure development. According to Seto and Hutya (2012), urban expansion is the physical growth of urban land into surrounding rural or natural areas, often driven by demographic and economic pressures. Similarly, the United Nations Department of Economic and Social Affairs (2018) defines urbanization as the process by which a growing proportion of a population lives in urban areas, along with the expansion of urban land cover. In the African context, the term urban varies significantly between countries but generally refers to areas characterized by higher population density, economic activity, and developed infrastructure (UN-Habitat, 2022). In Uganda, urban expansion specifically involves converting vegetated and agricultural lands into built-up environments—residential, industrial, and infrastructural reflecting both demographic growth and policy-driven urban development (Ministry of Lands, Housing & Urban Development, 2022). While urban growth fosters economic innovation and poverty reduction, it also presents challenges for environmental sustainability and carbon sequestration, making its spatial assessment essential for sustainable city planning (Ministry of Lands, Housing & Urban Development Uganda State of Urban Sector Report, 2022).

#### 2.1.2 Carbon sequestration in urban areas

Urban areas are reserve areas for CO<sub>2</sub> mainly through the atmosphere and terrestrial biotic environments. A significant portion of the terrestrial carbon is in trees, which is important in global warming and climate change mitigation. Forests and other green areas in urban settings that can photosynthesize absorb the free CO<sub>2</sub> in the atmosphere, stabilize it into more stable complex compounds, and contribute to their long-term storage (Tang et al., 2022). For this purpose, one of the most important strategies for global warming and climate change is absorption and storage of CO<sub>2</sub> in the forest ecosystem. This is described as carbon sequestration. Urban green spaces have an important position in the sequestration of CO<sub>2</sub> in the city centers. (Gül et al., 2009). Urban trees perform vital functions to increase and improve people's quality of life in the city centers. Urban trees also improve the city's aesthetic value in terms of visual and ecological aspects and reduce carbon dioxide emissions from several anthropogenic activities. The open and green spaces that

are important for the discipline of landscape architecture play a major role in improving urban ecosystems, such as the urban heat island effect, and carbon sequestration.

Uganda possesses significant carbon sequestration potential due to its diverse ecosystems, including tropical forests, wetlands, grasslands, and expanding agroforestry systems. Nationally, efforts to enhance carbon sinks are guided by policies such as the National REDD+ Strategy, the updated Nationally Determined Contributions (NDCs), and commitments under the AFR100 Initiative to restore 2.5 million hectares of degraded land by 2030. Despite this potential, Uganda faces increasing pressure from deforestation and land-use change, which are particularly evident in rapidly urbanizing areas like Jinja City. In Jinja, carbon sequestration capacity is under threat due to accelerated urban sprawl, infrastructure development, and the encroachment of wetlands and green spaces that historically served as vital carbon sinks.

The degradation of ecosystems along the Nile River, Lake Victoria basin and establishment sugarcane plantation in areas of kakira which is in the city's vicinity has reduced the effectiveness of natural carbon storage, while weak enforcement of environmental regulations and insufficient integration of climate resilience into urban planning further exacerbate the problem. Although some localized reforestation and urban greening initiatives exist, they remain limited in scale and impact. For Jinja City to meaningfully contribute to Uganda's carbon sequestration goals, there is a pressing need to strengthen climate-smart land use policies, protect remaining wetlands and peri-urban forests, and mainstream nature-based solutions into urban development plans.

## 2.2 Spatial Trends of Urban Expansion in Jinja City

### 2.2.1 Spatial analysis techniques used to study urban expansion

Urban expansion is a dynamic spatial phenomenon characterized by the outward growth of cities, often resulting in land use transformation, environmental degradation, and infrastructural pressure. Understanding this growth requires robust spatial analysis techniques that can detect, measure, and model the patterns and drivers of urban change over time. Recent advances in geospatial technologies, including remote sensing, Geographic Information Systems (GIS), and spatial modelling, have significantly enhanced our ability to monitor and interpret urban growth processes with precision and scale. One of the most foundational tools in urban expansion analysis is remote sensing, which allows for the extraction of land use/land cover (LULC) data over multiple periods.

Multi-temporal satellite imagery from sources such as Landsat has been widely used to classify urban versus non-urban land through methods like supervised classification, object-based image analysis, and, more recently, machine learning classifiers (Weng, 2012; Singh et al., 2015). This enables researchers to detect and quantify changes in the spatial footprint of urban areas. For example, the Urban Land Index (ULI) and Urban Expansion Index (UEI) are often used to extract built-up areas in urban contexts (Zha et al., 2003).

several spatial indices have been developed specifically to quantify the intensity, direction, and form of urban expansion. One such measure is the Urban Expansion Index (UEI), which compares the rate of urban area growth to the rate of population increase, thereby revealing whether spatial growth is occurring in proportion to demographic trends (Liu et al., 2010). A UEI greater than 1 suggests urban sprawl, indicating that land is being consumed at a rate faster than population growth justifies. This index is particularly useful for policy assessments where urban efficiency is of concern. Another key measure is the Urban Land Index (ULI), which reflects the proportion of urban land to total available land within a given administrative boundary or buffer zone. ULI helps determine the degree of land consumption and the saturation level of urban development (Li et al., 2016). When integrated with time-series data, ULI can indicate trends in land densification or expansion and is often used in conjunction with urban form metrics, such as compactness and dispersion indices.

In conclusion, the spatial analysis of urban expansion has evolved into a multidisciplinary domain, leveraging remote sensing, GIS, spatial statistics, and computational modeling. Tools such as the Urban Expansion Index (UEI) and Urban Land Index (UI) play critical roles in quantifying and interpreting urban growth, while advanced geospatial techniques enable more nuanced and predictive analysis. Together, these approaches support more informed urban planning, sustainability assessments, and policy development in the context of rapid urbanization.

### 2.2.2 Urban Expansion in East Africa

East Africa is experiencing rapid urbanization, with an estimated rate of 4.6% as of 2018. Uganda is leading this trend with the highest urban growth rate of 6%, and it is projected to be one of the most urbanized nations in Africa by 2050. This urban expansion, fueled by significant population growth, migration from rural to urban areas, and infrastructure development, often proceeds in an

unplanned and informal way, resulting in the encroachment on sensitive environmental zones like wetlands and forests (UN-Habitat, 2020; Seto et al., 2012). As one of the fastest urbanizing countries in Sub-Saharan Africa, Uganda has an annual urban growth rate exceeding 5%. Cities such as Kampala, Wakiso, and Jinja are undergoing considerable spatial changes predominantly without adequate planning (UBOS, 2023; Lwasa, 2011).

This urban sprawl is marked by low-density development, the conversion of agricultural land and greenery into built environments, and escalating pressure on ecological systems, which increases vulnerability to climate-related risks like flooding, heat stress, and biodiversity decline (NEMA, 2019; Otieno & Ouma, 2021). In Jinja City, urban growth has followed a peri-urban pattern, with research indicating significant land use transformations, particularly the decline of wetlands and riparian vegetation along Lake Victoria and the Nile River, both of which play vital ecological and climate-regulatory roles (Kaggwa et al., 2021; Twongyirwe et al., 2019). Despite Uganda's policy frameworks, such as the National Urban Policy and the National Climate Change Policy, which promote sustainable urban development, enforcement at the city level is inadequate, leading to unregulated sprawl and increased climate vulnerability (MWE, 2015; MoLG, 2017).

## 2.3 Spatial Trends of Carbon Sequestration in Jinja City

### 2.3.1 Carbon sequestration in natural ecosystems

According to (IPCC, 2021) carbon sequestration refers to the process involving carbon capture and long-term storage of atmospheric carbon dioxide. Carbon sequestration is classified into terrestrial carbon sequestration, geological Carbon Sequestration, and technological Carbon Sequestration (Lal, 2008). Terrestrial sequestration, also termed "biological sequestration" is typically accomplished through forest and soil conservation practices that enhance the storage of carbon (such as restoring and establishing new forests, wetlands, and grasslands) or reduce carbon dioxide emissions (such as reducing agricultural tillage, fossil fuel use reduction and suppressing wildfires). Green plants are a natural carbon sink and play a huge role in controlling carbon dioxide. This is accomplished through photosynthesis. The process of photosynthesis occurs in the cells of photosynthetic organisms and within the leaves of a plant (Spellman, 2024). The process involves the conversion of light energy into chemical energy by plants. Plants and trees absorb huge amounts of carbon dioxide from the atmosphere during photosynthesis, incorporating some

of that carbon into structures such as wood, long-chained carbohydrates, and lignin. As a result of this process, plants play a significant role in mitigating climate change.

### 2.3.2 Impact of urban expansion on carbon sequestration

As the global carbon budget shrinks, urgent action is needed to reduce greenhouse gas (GHG) emissions and enhance carbon sinks to limit global warming below 1.5°C, according to the IPCC (2022). Urban areas, responsible for over 70% of worldwide CO<sub>2</sub> emissions, are increasingly seen not just as major emitters but also as potential carbon sinks through biogenic sequestration methods (Seto et al., 2014; Bai et al., 2018). This dual role makes cities central to climate mitigation, requiring a redesign of urban spaces to balance development with ecological resilience. Urban green infrastructure like forests, parks, gardens, wetlands, and farmland helps absorb atmospheric CO<sub>2</sub> and store it in biomass and soils, strengthening the city's carbon storage capacity (Churkina et al., 2020; McHale et al., 2017). Yet, in many fast-growing regions such as Uganda, urban expansion often reduces these natural sinks. In Jinja City, the spread of built-up areas has markedly altered land cover, decreasing green spaces including wetlands, farmland, urban forests, and private gardens (Twongyirwe et al., 2019; NEMA, 2019). Remote sensing over the past twenty years shows an increase in impervious surfaces, pointing to more industrial, residential, and infrastructural growth (Mwesigye et al., 2020). This change has heavily fragmented green areas and damaged peri-urban ecosystems, which previously played key roles in carbon storage and microclimate control.

The loss of these green spaces is directly linked to decreased local carbon sequestration potential. Studies have shown that urban vegetation and wetlands in East African cities contribute significantly to biogenic carbon uptake, especially in urban peripheries where vegetation is more dense (Lwasa et al., 2014; Baganizi et al., 2021). In Jinja, the conversion of wetlands and forests along the Nile River and Lake Victoria basin to residential and industrial land use has diminished the city's ecological resilience and its capacity to act as a carbon sink. Furthermore, this land use change has been accompanied by increased anthropogenic emissions from motorized transport, construction, and industrial processes, exacerbating the city's carbon footprint (Otieno & Ouma, 2021).

The growing conflict between urban expansion and ecological health in the face of climate change is becoming more critical. Without climate-conscious land use planning, urban growth damages carbon storage, boosts emissions, and increases vulnerability to hazards like heat islands and flooding (Douglas et al., 2008; Churkina et al., 2020). Thus, it is vital for cities like Jinja to conduct thorough carbon inventories that evaluate the sequestration capacity of existing green spaces. These inventories can guide land use policies that focus on conserving and enhancing high-capacity sequestration areas, fostering urban greening, and incorporating ecosystem-based adaptation into urban development (UN-Habitat, 2021; NEMA, 2019). By adopting climate-sensitive urban planning, Jinja can support Uganda's national climate goals outlined in the latest NDCs and Climate Change Policy (MWE, 2015). This involves protecting wetlands, expanding urban forestry, and restoring degraded ecosystems as nature-based solutions to reduce emissions and boost urban resilience. Achieving a net carbon sink in Jinja's urban system will require coordinated efforts in spatial planning, governance, community involvement, and data-driven strategies that prioritize climate mitigation and resilience.

### 2.3.3 Previous studies on carbon sequestration in other cities

A study conducted in Juba City South Sudan shows that Trees in the city of Juba removed 30,506 tonnes C yr<sup>-1</sup> (Carrillo & Garijo, 2020). This amount is equivalent to the carbon dioxide emitted by 6632 passenger vehicles annually. The study also showed that Urban trees provide a natural and cost-effective alternative to capture and store carbon in cities. Having trees in densely populated areas also improves human health and biodiversity and provides benefits for flood prevention and reduced cooling costs, among other benefits.

(Berglihn & Gomez-Baggethun, 2020) estimated the average gross carbon storage of trees in the urban fringe forest of Oslomarka in Norway at 10.3 kg C/m<sup>2</sup>, with annual gross sequestration of 0.1 kg C/m<sup>2</sup>, though they note that their estimates are subject to high uncertainty. Linden et al (2020) estimated the aboveground gross carbon storage of urban parks in Helsinki at 2.21–2.81 kg C/m<sup>2</sup>, highlighting the impact of coarser tree cover compared to the urban remnant and fringe forests. Ariluoma et al (2021) approximated that the gross tree sequestration of 0.12 kg C/m<sup>2</sup>/a which could be amplified to 0.23 kg C/m<sup>2</sup>/a with biochar amendment in semi-public residential yards, resulting in average gross tree carbon storage of 5.94 kg C/m<sup>2</sup> and 11.4 kg C/m<sup>2</sup> during the 50 year study period, respectively. Finally, Riikonen et al (2017) highlighted that the emissions

from the growing medium need to be accounted for when estimating the life cycle CSS impact of tree planting, as the planted street trees acted as emissions sources rather than carbon sinks during the early years after their establishment, resulting in average annual emissions or negative net sequestration of 1.3 kg C/m<sup>2</sup>/a.

## 2.4 Drivers of Urban Expansion

Urban expansion is a complex process shaped by demographic, economic, infrastructural, and institutional factors operating across different spatial and temporal scales. Demographically, rapid population growth and rural–urban migration are primary drivers, particularly in developing countries, where rising populations increase the demand for housing, employment, and services. This often leads to the transformation of agricultural and vegetated lands into built-up areas (Seto, Güneralp, & Hutyra, 2012; United Nations, 2018). Economic development and industrialization further accelerate this pattern, with cities becoming centers for trade, industry, and jobs that attract investment and promote spatial growth (Angel, Parent, Civco, & Blei, 2016). Urban expansion typically follows accessibility routes and infrastructure such as roads, bridges, and energy networks, which reduce travel times and stimulate residential and industrial development in peri-urban areas (Abebe & Megento, 2017; Kombe, 2019). At the same time, weak urban governance and lax land-use regulation enforcement can lead to unplanned sprawl, especially in regions where traditional land tenure systems are dominant.

Like many secondary cities in Sub-Saharan Africa, Jinja City's urban growth is fueled by a combination of socio-economic, demographic, political, and infrastructural factors. A primary driver is the rapid increase in population, resulting from natural factors such as high fertility, low mortality rates, and rural-to-urban migration. Uganda's high population growth rate makes cities like Jinja attractive to migrants seeking improved services (UBOS, 2023; Lwasa, 2011). This demographic trend has boosted demand for housing and essential services, often leading to informal, unplanned settlements on the outskirts, mainly due to weak enforcement of planning laws (NEMA, 2019). Besides demographic influences, economic development significantly influences Jinja's urban growth. Recent years have seen a revival in economic activity driven by government efforts to decentralize development from Kampala and encourage regional growth.

The emergence of industrial parks and investments in manufacturing and agro-processing industries have established the city as a regional economic hub (Mwesigye et al., 2020). This economic shift has attracted workers from nearby rural areas, spurred land speculation, infrastructure projects, and transformed farmland and forests into residential and commercial developments.

Furthermore, urban populations driven by consumption are characterized by evolving, wasteful lifestyles, increased vehicle ownership, and a rising demand for modern infrastructure, all of which have sped up the expansion of built-up areas. As middle-income groups grow, there is greater demand for larger, better housing, shopping centers, and road networks. This results in horizontal urban sprawl rather than vertical, compact development (Seto et al., 2012; UN-Habitat, 2020). Unfortunately, this growth often occurs without proper infrastructure planning, leading to settlements with limited water, sanitation, and paved roads, which exert pressure on ecosystems like wetlands, forests, and rivers (Twongyirwe et al., 2019). Governance and institutional issues also significantly influence urban expansion in Jinja. Weak enforcement of land use regulations, fragmented planning, and unclear land tenure systems foster uncontrolled land development and encroachments on ecologically sensitive areas (MoLG, 2017; Nuwagira et al., 2022). The city's planning bodies frequently lack the technical and financial capacity to promote sustainable urban growth, allowing informal land markets to flourish and undermining long-term spatial planning goals.

In summary, the urban expansion of Jinja City is a product of interrelated demographic, economic, socio-cultural, and governance drivers. While population growth and industrialization fuel spatial expansion, the lack of adequate planning and governance mechanisms has led to sprawling, infrastructure-deficient, and ecologically vulnerable urban forms. Understanding these drivers is critical for designing sustainable, climate-resilient urban strategies that align with national development goals and global climate commitments.

## 2.5 Implications of Urban Expansion on Carbon Sequestration

It's unequivocal that human activities are causing climate change (IPCC, 2022). Some empirical pieces of evidence include climate extreme events, including heatwaves, heavy rains, and frequent but also severe droughts. Recent climate-related disasters are diverse, sudden, and growing in

aggressiveness. The chances of reversing some of these changes are minimal however, some changes can be stopped or slowed down by limiting global warming(IPCC, 2022). This can be done only if there are strong, rapid, and sustained reductions in the concentration of carbon dioxide. Urban centers cover 0.4–0.9% of the global land surface(United Nations, 2018). And over half the world’s population lives in towns and cities. Cities and towns generate approximately three-quarters of the global total carbon emissions from energy use(UNFCCC, 2021).

## 2.6 Relationship Between Urban Expansion and Carbon Sequestration

### 2.6.1 Quantitative assessment of carbon sequestration rates

In recent years, remote sensing (RS)-driven physiological process models with simple, generic structures have become the main choice for simulating the spatiotemporal dynamics of vegetation carbon dioxide fluxes. The growing availability of multi-source RS data, both commercial and open-source, provides visual information for understanding ecosystem dynamics and evolutionary processes. Inputs from RS data, such as vegetation indices and vegetation phenology, supply the physiological parameters and environmental variables necessary for cross-scale model simulations, enhancing the accuracy of carbon dioxide flux estimates. The normalized difference vegetation index (NDVI) is a key index for studying vegetation and forest dynamics, and it will be used in this research. NDVI can help estimate net primary productivity (NPP) and above-ground biomass (AGB), which are indicators of carbon sequestration through the CASA.

### 2.6.2 Relationship between urban expansion and carbon sequestration

Humans and their natural interaction with the environment explain the changes in land cover over time. Humans have significantly impacted land cover through the well-known process of urbanization. As urban centers grow, increased pressure from the expanding population often leads to land cover and land use changes such as infrastructural development, agricultural expansion, and energy needs. These changes create competition for space with natural resources like forests and green areas. Urban expansion often results in a reduction of forest cover due to increased urban growth, waste production, pollution, and environmental decline. Understanding urbanization and its effects on carbon sequestration offers valuable insights for planning green cities and developing strategies to address global climate change. Using tools like remote sensing, machine learning, and GIS can be highly effective in studying the link between urbanization and carbon sequestration by generating land cover maps.

## 2.7 Integrated Assessment of Urban Expansion and Carbon Sequestration

### 2.7.1 Frameworks for assessing urban expansion and carbon sequestration

Natural and anthropogenic factors primarily drive carbon dioxide flux dynamics in vegetative ecosystems. Climatic variables, particularly temperature and precipitation, affect NPP by altering plant physiological and ecological processes and regulating community biomass. Elevation affects NPP by altering the local microclimate. Anthropogenic activities, with a dual impact on NPP, are often indirectly described using land use and land cover change. For instance, grassland degradation and urbanization increase carbon emissions, whereas reforestation and afforestation enhance carbon sequestration. Although the dynamic response of NPP to natural factors and LUCC has been a focus of ecological studies, different research tools, seasonal differences, and single vegetation types have led to inconsistent and incomplete results of regional studies. Considering the impacts of extreme climate and ecological construction, it is increasingly urgent to uncover the intrinsic drivers of vegetation NPP

The term remote sensing was first used in the early 1960s. Later, it was defined as the different processes involved in acquiring and measuring information of some property of objects and phenomena by a recording device (sensor) that is not in physical contact with the objects and phenomena in the study. Currently, with the advancement in satellite technology and the development of various complex software used in remote sensing, it has been applied in environmental processes such as agriculture, land cover, vegetation dynamics, water quality, urban growth, and disaster management (Gülçin & Konijnendijk, 2021). Remote sensing cannot be underestimated in understanding the complex trends in urban expansion and how it is affecting the levels of carbon sequestration on spatial and temporal scales. In developing countries like Uganda, remotely sensed data of good quality may not be easily available yet it is important to have good multi-temporal data to analyze land cover changes as a result of urbanization.

The urban land index and urban expansion index will be used to measure the urbanization of Jinja City (Haas, 2016). Using multi-temporal data, urban indices have been created to quantify urban land cover and change patterns over time. The urban land index is defined as the ratio of urban land to total land at a specific point in time. The urban expansion index compares the amount of urban land at two different time points. It is simply a relative measure of the speed of urbanization. This research will use both indices to study the characteristics of Jinja City's urban environment

and the rate at which urbanization occurs. Current studies indicate that carbon sequestration in urban areas can be studied, monitored, analyzed, and mapped using remote sensing technology. This can be achieved through high- and medium-resolution Landsat images. (Carrillo et al., 2020) assessed carbon storage in Juba City, the capital of Sudan, using remote sensing and found that tree vegetation in Juba City removed 30,506 tonnes of C per year, which significantly contributed to reducing greenhouse gases in the atmosphere and helped mitigate climate change.

One of the most important uses of remote sensing is the production of Land Use / Land Cover maps this can be done through a process called “Image Classification”(Jwan Al-doski, 2013). Image Classification has made great progress over the past decades in producing land cover maps at regional and global scales. This is possible through the development and use of advanced classification algorithms and knowledge-based classification algorithms, the use of multiple remote-sensing features, including spectral, spatial, and multitemporal information, and the incorporation of ancillary data into the classification procedure(Ponnusamy .R, 2017). There are several types of image classification but one broad type of classification will be considered in this research, which is supervised classification. Supervised classification is based on the idea that a user can select sample pixels in an image that are representative of specific classes and then direct the image processing software to use these training sites as references for the classification of all other pixels in the image. Training sites are selected based on the knowledge of user. The user also sets the bounds for how similar other pixels must be to group them. These bounds are often set based on the spectral characteristics of the training area, plus or minus a certain increment.

### 2.7.2 Policy implications for sustainable urban planning

Over the past 30 years, urban planning policies have played a vital role in reducing the environmental impacts of urbanization. Sustainable urban planning aims to balance the needs of city growth with environmental conservation, ensuring that cities remain liveable while decreasing their carbon footprint. In Uganda, the National Urban Policy highlights the importance of green infrastructure and maintaining natural spaces within urban areas. Environmental sustainability has become one of the most important areas of focus for sustainable development. The Rio Summit, with its Agenda 21 Principles for Action, has influenced urban planners and the Local Agenda 21 movement. Recently, there is a growing acknowledgment of climate change as a major new

challenge faced by both global and local communities. Cities use and exhaust huge amounts of resources and energy.

Environmental crises are created by waste and refuse processing and conflict is generated over the limited natural resources available to urban residents. Risk and vulnerability, especially of the poorest, is increasing, particularly in the face of extreme weather phenomena brought about by climate change. Although it is widely recognized that traditional urban planning models and approaches have contributed to the present environmental crisis, it is also clear that addressing environmental issues at city level will not be possible without appropriate urban planning systems that integrate respect for the natural environment with the improvement of the human environment and reduction of greenhouse gas emissions of cities. The pursuit of carbon-neutral cities, through the increase in green areas within cities and the use of ecological services, often combined with efforts to close the energy/materials loops of cities, decentralize renewal energy production, and reuse waste, has recently emerged as a way to increase synergies between build and natural environment in cities. Patterns of urban growth can be influenced to reduce carbon emissions, by promoting more compact cities and ensuring better access to collective or non-motorized transport. Resilience to potential environmental disasters can be increased through proper urban and land use planning. Nowadays, planning and managing urban trees have been becoming increasingly important. At the same time, urban trees have been coming to the fore with using, sharing, and evaluating of monetary and non-monetary services and contributions. In particular, city administrators, planners, and researchers demand that the current state of urban trees and forests be learned, and their values provided to the urban ecosystem be explored and applied. However, there is a growing need to assess the effectiveness of these policies in fast-growing cities like Jinja.

## 2. 8 Research Gaps

Although urban expansion and its environmental impacts in sub-Saharan Africa are gaining more attention, significant research gaps remain, particularly regarding how urban growth influences carbon sequestration over time in secondary cities like Jinja. In Uganda, most studies on urbanization focus on growth drivers, land use changes, and challenges related to informal settlements (Lwasa, 2011; Mwesigye et al., 2020). However, few include ecosystem carbon dynamics in spatial planning discussions. Even when spatial analysis is employed, it often lacks the temporal dimension necessary to track how land cover changes especially the transformation

from vegetation and greenspaces to built-up areas impact the city's capacity to act as a carbon sink over time. Global and regional research emphasize the role of urban green spaces, wetlands, and forests in carbon storage (Churkina et al., 2020; McHale et al., 2017), but high-resolution, localized studies of these functions in Jinja are limited. Additionally, there is a lack of quantitative estimates regarding carbon stock loss or sequestration potential under various urban growth scenarios. Most environmental assessments in Uganda, like those by NEMA (2019), focus on overall environmental degradation without connecting land use changes to carbon accounting, reducing their effectiveness for climate mitigation planning.

Moreover, Jinja City's current spatial planning rarely integrates carbon sequestration data into land use policies. Tools like carbon inventories, sequestration models, or ecosystem service valuations are seldom used in urban development plans. This reveals a larger institutional and technical gap, where urban planning authorities lack access to spatial decision support systems that combine land use, demographic, and carbon information (UN-Habitat, 2021). As a result, urban growth continues to threaten high-value ecological zones, leading to increased carbon emissions and undermining Uganda's climate commitments under the Paris Agreement and its updated NDCs (MWE, 2020).

## CHAPTER THREE RESEARCH METHODOLOGY

### 3.1 Introduction

This chapter focused on the data types used, sources of data, techniques, approaches, methods of field surveys for ground truthing, reference data for determination of how urban expansion is affecting carbon sequestration, change detection methods, algorithms for image classification, accuracy assessment, and list of software and tools used in the analysis of remotely sensed images.

### 3.2 Research design

The study employed a spatial–temporal quantitative research design to evaluate the impact of urban expansion on carbon sequestration in Jinja City between 2001 and 2021. This approach was suitable because it allowed the integration of remote sensing and GIS techniques to analyze spatial patterns and temporal changes over two decades (Lwasa, 2010; Seto et al., 2012). Multi-temporal Landsat images (Landsat 7 ETM+ for 2001, Landsat 8 OLI for 2021, and an intermediate image from around 2011) were obtained from the USGS EarthExplorer platform to map land use and land cover (LULC) changes (USGS, 2021). The images were chosen from cloud-free, end-year dry season periods to ensure consistency and reduce seasonal variations in vegetation reflectance (Mugagga et al., 2017). Ancillary datasets, including the Jinja City administrative boundary shapefile, major roads, and city center coordinates, were used to spatially limit the analysis, while monthly climatological variables temperature, precipitation, and solar radiation were collected from NASA and local meteorological stations (Potter et al., 1993). These datasets provided crucial inputs for the Carnegie Ames Stanford Approach (CASA) model used to estimate vegetation productivity and carbon sequestration. The study used QGIS for spatial data processing and R software for statistical and modeling analysis to ensure accuracy, reproducibility, and flexibility in data management (R Core Team, 2023).

Data preprocessing and classification formed the basis for evaluating urban expansion. All satellite images were radiometrically and atmospherically corrected and aligned to a consistent coordinate system to ensure comparability over time (Chander, Markham, & Helder, 2009). Supervised image classification was performed using the Random Forest algorithm to categorize the study area into five main classes: urban/built-up areas, trees, bare land, water bodies, and agricultural land (Belgiu & Draguț, 2016). Training samples were obtained from high-resolution Google Earth imagery and

field observations to improve classification accuracy. The accuracy of each classified image was validated with a confusion matrix, and only classifications with an overall accuracy above 85% and a Kappa coefficient above 0.8 were accepted (Congalton & Green, 2019). Change detection techniques were applied to the classified maps to assess the extent and direction of urban growth between 2001 and 2021. The urban expansion rate was calculated, and spatial analyses such as zone analysis were used to characterize the growth pattern (radial, linear, or clustered) and identify key expansion zones within the city (Angel et al., 2011).

To analyze carbon dynamics, the study used the CASA model to estimate Net Primary Productivity (NPP) as a measure of carbon sequestration (Potter et al., 1993). NDVI values from Landsat images were used to estimate the fraction of photosynthetically active radiation absorbed by vegetation, while temperature, precipitation, and solar radiation data were used to calculate light-use efficiency and stress factors (Field et al., 1995). The model generated annual NPP raster maps showing the amount of carbon fixed by vegetation (in  $\text{gC}/\text{m}^2/\text{year}$ ). Additionally, aboveground biomass and carbon stock were estimated by assigning literature-based carbon densities to each vegetation class derived from the LULC maps (IPCC, 2006). This approach was similar to the InVEST Carbon Storage model, enabling the estimation of total biomass carbon for each period (Sharp et al., 2018). The study then examined spatiotemporal trends in NPP and biomass carbon from 2001 to 2021 to assess the extent of vegetation degradation and loss of carbon sequestration potential due to urban expansion (Yao et al., 2019).

Finally, the study examined the relationship between urban expansion and carbon sequestration by integrating the urban and carbon datasets. Spatial overlay analysis identified areas that transitioned from vegetated cover in 2001 to built-up areas by 2021, allowing direct estimation of carbon loss due to land conversion (Seto, Guneralp, & Hutyra, 2012). Statistical correlation and regression analyses were conducted in R to quantify the inverse relationship between the proportion of urban area and total vegetation carbon stock (Zhao et al., 2021). The final results were presented through thematic maps, graphs, and statistical summaries showing the spatial and temporal interplay between urban growth and carbon decline. This integrated research design provided a comprehensive framework for understanding how rapid urbanization has altered the ecological carbon balance of Jinja City and contributed to reduced carbon sequestration capacity over the two-decade period.

### 3.2.1 General methodology of this research

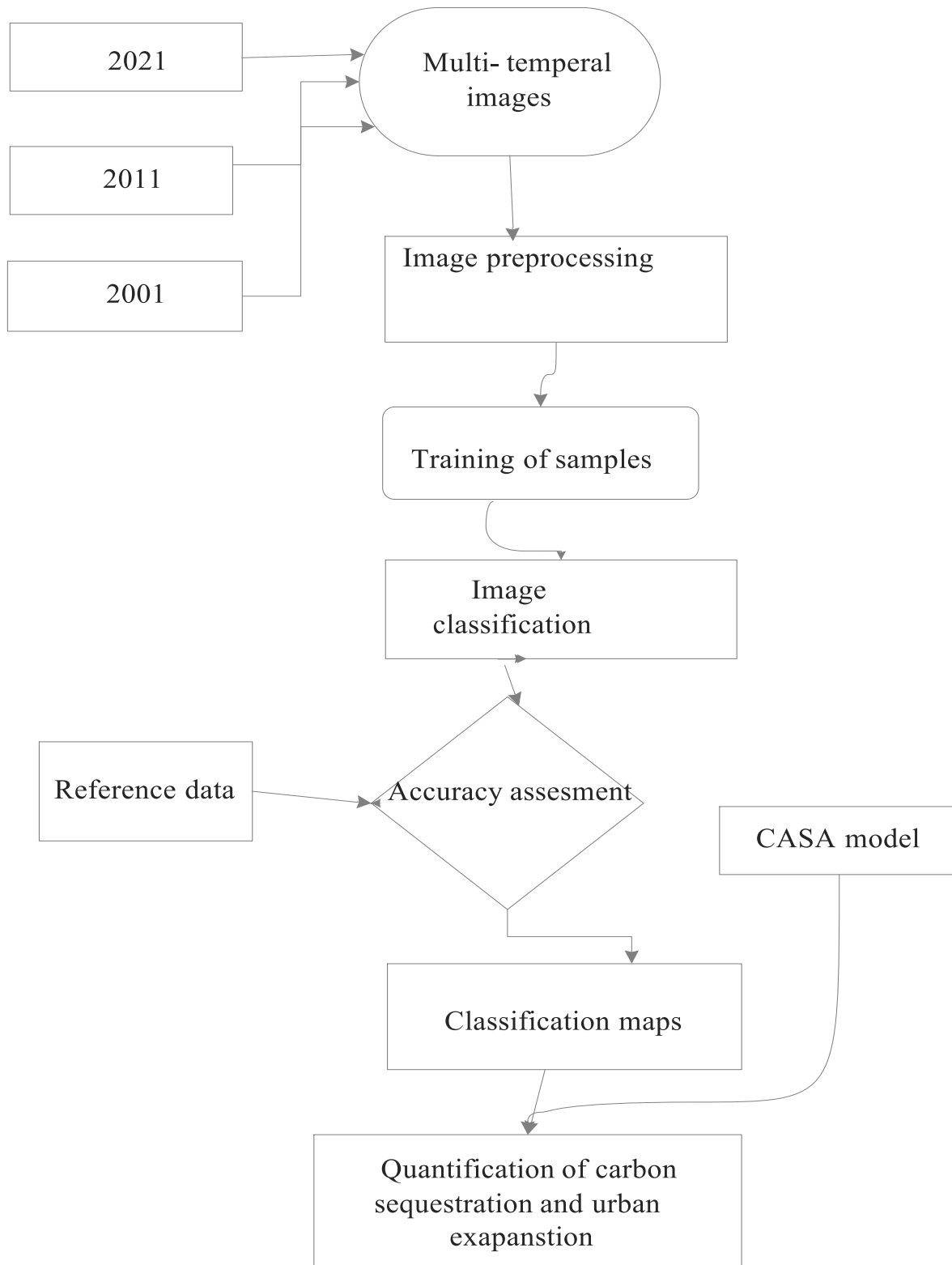


Figure 1: General methodology

### 3.3 Description of the area of study

Jinja City is in southeastern Uganda at roughly 0.4479° N and 33.2025° E, about 80 km east of Kampala. Located at 1,204 meters above sea level on Lake Victoria's northern shores and along the River Nile's source, it is one of Uganda's most scenic and strategic towns. Jinja is divided into two main divisions: the Southern Division, including the former Jinja Municipality, and the Northern Division with Bugembe Town Council, Budondo Subcounty, and Mafubira Subcounty. It borders Jinja District to the north and east, with urban growth along transport routes and peri-urban settlements. Its proximity to the Nile influences land use, climate, and urban development.

Jinja City features gently rolling terrain with low hills and valleys draining into Lake Victoria and the Nile. Its elevation provides moderate slopes suitable for agriculture and urban growth, though some areas may experience runoff and erosion during heavy rains. The soils are mainly ferrallitic and loamy, supporting diverse farming, especially in peri-urban zones with mixed agriculture. Native vegetation includes tropical moist savanna, woodland, and riparian species. Much of the original forest and wetlands has been lost or degraded by urban expansion, agriculture, and industry. Urban green spaces now mainly consist of remaining trees, gardens, roadside vegetation, and buffer zones along the Nile and its tributaries.

Jinja experiences a tropical rainforest climate shaped by its closeness to Lake Victoria. The city's average temperatures vary between 20 °C and 30 °C, with minimal daily fluctuations thanks to the lake's thermal influence. Annually, about 2,111 mm of rain falls, predominantly during two rainy seasons from March to May and September to November while the months of January–February and June–August are typically drier. During the wettest months, rainfall can reach up to 255 mm, fostering lush vegetation and supporting agriculture. Additionally, winds and high humidity influence evapotranspiration patterns, which are crucial for plant growth.

Jinja's economy is diverse, blending industrial, commercial, agricultural, and service sectors. It is Uganda's industrial hub, with industries like textiles, steel, breweries, and agro-processing mainly in the Southern Division and near the Nile. Hydropower from Nalubaale and Kiira dams boosts Uganda's electricity. In peri-urban and northern areas, subsistence and commercial farming grows crops like maize, cassava, bananas, sugarcane, and vegetables. Fishing on Lake Victoria and the

Nile supports food and income. Tourism, known for white-water rafting, bungee jumping, and cultural activities at the Source of the Nile, is expanding. These activities shape land use, urban growth, and influence carbon sequestration potential.

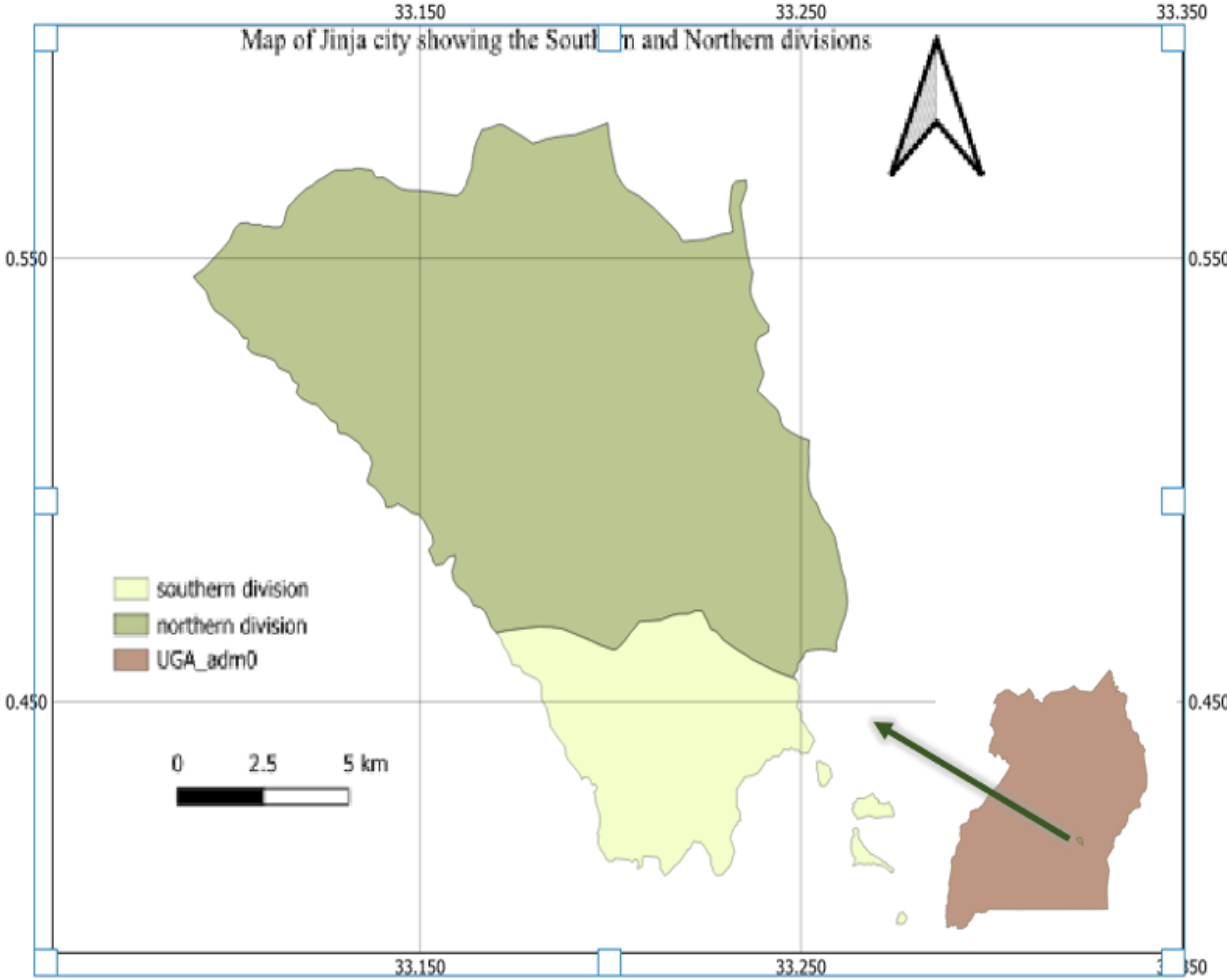


Figure 2: Study of the area

### 3.4 Description of population

The second-largest city in Uganda, Jinja, has a population of slightly over 292,386, according to the 2024 census. However, the city administration's statistics estimate that Jinja's current daytime population swells by almost 70,748 when other groups of people in the city are counted, including unregistered residents, those who reside just outside the official city boundary, and those who commute daily to conduct business and utilize city services (Jinja City Council, 2024).

### 3.5 Sampling techniques

#### 3.5.1 Cluster Sampling for Urban Expansion Areas

Jinja city with different rates of urban expansion across zones, and cluster sampling focused resources on localized areas where urban expansion was most intense. Jinja City was divided into clusters based on areas of rapid expansion, moderate growth, and stable zones. Within each cluster, randomly select specific sites for data collection. This included newly urbanized areas, bare land areas, grasslands, and green areas.

#### 3.5.2 Temporal Sampling for Time-Series Analysis

This was used to capture the changes in carbon sequestration over time. Temporal sampling at ten-year intervals revealed trends and patterns for the specified time period. Satellite images and remote sensing data were analyzed over a period of 10-year intervals to observe urban expansion and vegetation changes, with sample plots measured for carbon sequestration rates each period. This sampling approach helped to understand both the short-term and long-term impacts of urban growth on carbon sequestration in Jinja City.

The study employed a time-series approach using multi-year Landsat TM/ETM+/OLI-derived NDVI and surface temperature data, which were processed through the CASA light-use efficiency model (Zhu et al., 2017). Annual compositing, combining multiple satellite images each year to minimize cloud noise and seasonal effects, was performed. The key years selected, 2001, 2011, and 2021, were chosen to align with decadal urban expansion phases in Uganda and to ensure consistent seasonal data for NPP and AGB modelling. For urban expansion and built-up area indices, annual proportions of built-up land across all 21 years were calculated, and a spatial-temporal buffer analysis was used to develop a decadal urban expansion index that captures both extent and fragmentation. Trend detection employed methods such as annual time-series aggregation and breakpoint-aware slope fitting, which effectively handle inter-annual NDVI fluctuations. This structured framework of temporal sampling enabled the accurate detection of both gradual and sudden ecological changes, with decadal snapshots enhancing interpretability in the context of urbanization.

### 3.6 Data collection methods

#### 3.6.1 Remotely sensed data

Remotely sensed images were obtained from the United States Geographical Survey (USGS) website with medium-resolution images of 30m. Three images were collected for 2021, 2011, and 2001. All the images were selected from the same season of March to May based on the fact that the region always receives rain during this time. The cloud cover in the images was less than 10 percent to improve accuracy during classification and NDVI calculation. GIS data on boundaries and administrative areas of Jinja City were obtained from the websites [www.diva-gis.com](http://www.diva-gis.com) and [www.ugandaspatialsolutions.com](http://www.ugandaspatialsolutions.com), which were the source shape files. All the data sets were referenced in WGS 1984, UTS zone 36 projection systems. All spatial data were summarized in Tables 1 and 2 below.

*Table 1: Data sources, format, and acquisition date*

Satellite data	Date of acquisition	Data source
Landsat EMT+	27-11-2001	USGS
Landsat EMT+	9-12-2011	USGS
Landsat 8	12-12-2021	USGS
Precipitation data	November 2001 December 2011 December 2021	<a href="https://chrsdata.eng.uci.edu/">https://chrsdata.eng.uci.edu/</a> <a href="https://chrsdata.eng.uci.edu/">https://chrsdata.eng.uci.edu/</a> <a href="https://chrsdata.eng.uci.edu/">https://chrsdata.eng.uci.edu/</a>
Land surface temperature data	November 2001 December 2011 December 2021	Derived from Landsat EMT+ Derived from Landsat EMT+ Derived from Landsat 8
NDVI	November 2001 December 2011 December 2021	Derived from Landsat EMT+ Derived from Landsat EMT+ Derived from Landsat 8

*Table 2 spatial sources data*

Spatial data	Format	Data source
Administrative boundaries	Shape file	<a href="http://www.diva-gis.com">www.diva-gis.com</a>
Urban and built-up areas	Shape file	Derived
Urban vegetated area	Shape file	derived
City divisions	Shape file	derived
Meteorological data	Xlsx	Derived

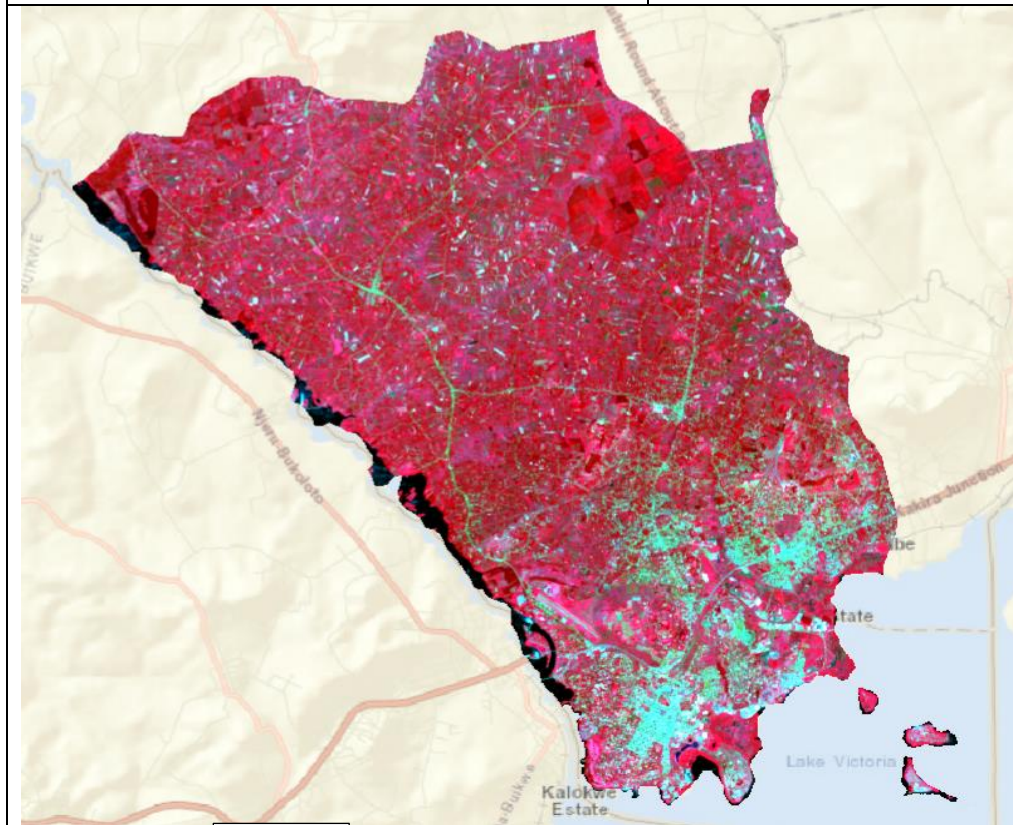
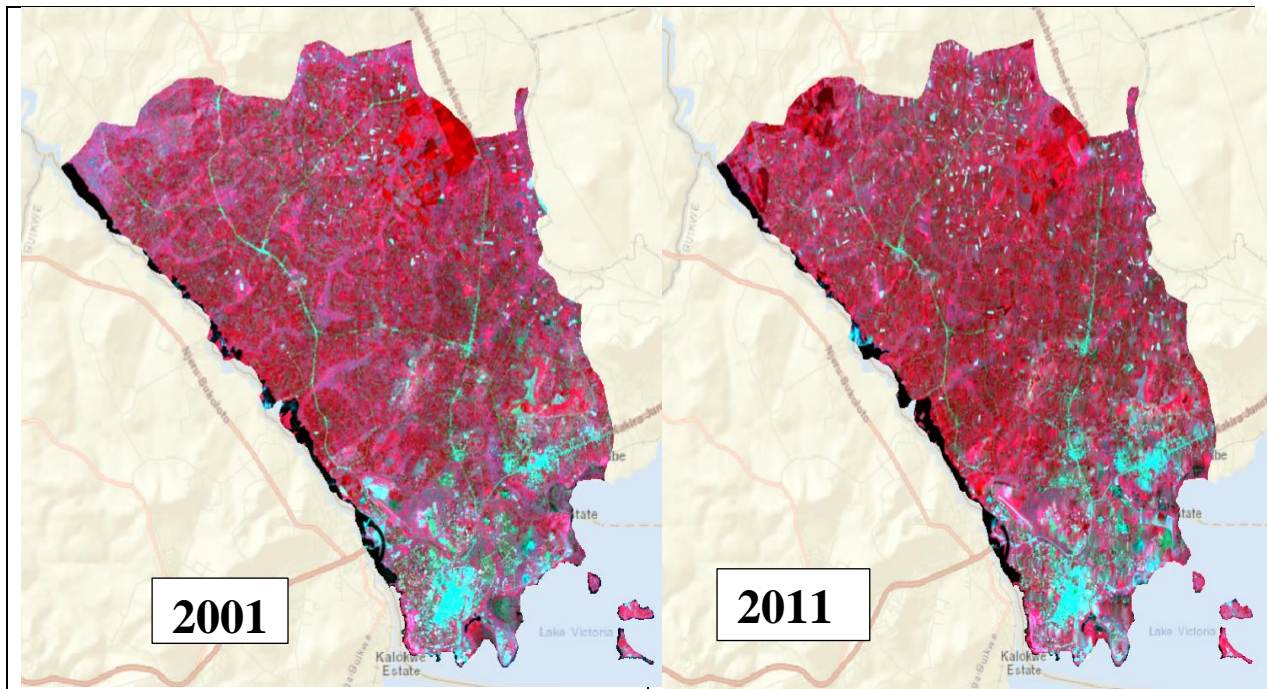


Figure 3 false **2021** composite of land sat images covering the study area for the years 2001, 2011, 2021

### 3.6.2 Field data

Both primary and secondary data was required to achieve all the study objectives. Secondary data was obtained from open-source websites and supplemented with field surveys. The field surveys were necessary for ground truthing and were used to determine the accuracy of classified imagery. The digital camera was used to take photographs of selected features, and a hand-held GPS device will collect the coordinates of ground control points.

### 3.6.3 Reference data

Ground truth data is important in the accuracy assessment of the classified map (Congalton & Green, 2019; Foody, 2002; Jensen, 2015). A total of 130 ground control points was used, covering all five landcover classes with particular emphasis on bare land and urban land cover classes due the similar spectral characteristics of these classes. Simple stratified random sampling was used to determine the location of the control points. And this was carried out with the help of local experts with more knowledge of the study area.

### 3.6.3 Data quality control

The data used for this research were primarily remotely sensed data. To ensure quality control, the remotely sensed images were obtained from the United States Geological Survey (USGS) website during the same period for the specified years. November and December were considered to reduce seasonal variability, as these are months of lower cloud cover due to the study area's proximity to Lake Victoria.

### 3.6.4 Measurements and Research Tools

The research instruments and tools designed for the study included a questionnaire, hand-held GPS machines, and literature search guides. The questionnaires were online and targeted experts in the environment, planning, and policy departments of Jinja City. Literature search guides were used for obtaining secondary data.

## 3.7 Data analysis

### 3.7.1 specific objective 1: Analyze the spatial trends of urban expansion in Jinja City

Raster satellite images and relevant remotely sensed data of Jinja City were obtained from USGS and Google Earth for analysis of the green areas of interest. This analysis was conducted to identify and monitor urban expansion at 10-year intervals, starting with 2001, followed by 2011 and 2021.

Classification of tree coverage and urban land was performed using supervised image classification, involving the design of multiple components to train machine learning algorithms, classify the image over the area of interest, and produce a visualization-ready tree cover map. Training of the algorithms using sample points collected through visual inspection from high-resolution Google Earth Images and field sample points was performed. A map was generated that includes other land cover categories such as water, grass, and built-up areas, which can also be useful for planning and other applications. The urban land index was calculated after classification to show the proportion of urban land relative to the total land in percentage. Additionally, the urban expansion index was computed to illustrate the variation of urban land over a given period.

The urban land index was calculated from

$$UI = \frac{UL}{TL} \times 100\%$$

Where  $UI$  is the urban land index,  $UL$  is the urban land area, and  $TL$  is the total land area

The urban expansion index was calculated from

$$UE = \frac{UL_{t2} - UL_{t1}}{TL} \times \frac{1}{T} \times 100\%$$

Where  $UE$  is the urban expansion index,  $UL$  is the urban land area,

The study combined quantitative GIS analysis with qualitative assessment of the drivers of change. The study examined the spatiotemporal dynamics of urban growth in Jinja City during this period. Using Landsat satellite images and pre-classified land cover maps, the study identified land cover changes, particularly urban expansion. For the years 2001, 2011, and 2021, the total area in hectares for each land cover class was calculated. By overlaying these maps, we pinpointed areas that transitioned into urban land. This allowed to quantify overall urban growth and track specific land conversions, such as forests and farmland turning into built-up areas. To provide a quantitative overview, The study used two indices the Urban Land Index (ULI), reflecting the percentage of land classified as urban annually, and the Urban Expansion Index (UEI), showing the percentage increase in urban land over time. These measurements align with the United Nations Sustainable Development Goal (SDG) Indicator 11.3.1, which relates land consumption to

population growth, offering insights into land use efficiency and urban planning (UN-Habitat, 2018).

3.7.2 specific objective 2: To quantify the spatial and temporal trends in carbon sequestration of urban green space of Jinja City.

The assessment of carbon sequestration was conducted based on two key indicators. NPP and AGB, calculated using the CASA (Schaefer et al., 2008).

Carbon sequestration estimation using the CASA model (Xu et al., 2023)

The classified Landsat rasters of years 2021, 2011, and 2001 were imported into R, an open-source software, and NDVI was calculated. Meteorological data will be obtained from meteorological stations around Jinja and from climate data websites, and some were derived from world climate datasets

The CASA model estimates GPP using NDVI and environmental parameters as simplified below.

$$\text{GPP} = \text{NDVI} \times \text{Temperature} \times \text{Precipitation}$$

After estimating GPP, we shall calculate NPP and ecosystem respiration. A common assumption is that respiration is a fixed percentage of GPP.

$$\text{NPP Calculation: } \text{NPP} = \text{GPP} - \text{Respiration}$$

Assumed Respiration Rate: For example, 40% of GPP.

Here's the general formula for estimating Above Ground Biomass (AGB) from NPP:

$$\text{AGB (kg)} = \frac{\text{NPP (g C/m}^2\text{/year)} \times \text{BGR}}{0.47}$$

Where:

- NPP (g C/m<sup>2</sup>/year): Net Primary Productivity from the CASA model.
- BGR: Biomass Growth Rate (the proportion of NPP that goes into biomass production).

- 0.47: Conversion factor for carbon content in biomass (since ~47% of biomass is carbon).

Generally, the carbon fraction in biomass is around 50% ( about half of the dry biomass is carbon).

This means you can convert NPP to carbon sequestration using the following formula

Carbon Sequestration (g C/m<sup>2</sup>/yr)=NPP (g C/m<sup>2</sup>/yr)×Fraction of Carbon

This study analyzed spatiotemporal trends in carbon stocks in Jinja City from 2001 to 2021 using outputs from the CASA model to estimate NPP, AGB, and carbon sequestration. The analysis included both trend evaluation and spatial mapping to understand changes over time. The CASA model, which simulates vegetation productivity using remote sensing and climate data (Potter et al., 1993), was employed to estimate carbon metrics. NPP and AGB outputs were validated for accuracy in the Jinja context. NPP maps were created for 2001, 2011, and 2021, and AGB maps were derived from NPP with biomass factors. An annual time series of carbon stock estimates was assembled when possible, providing up to 21 observations for long-term trend analysis.

The study examined temporal dynamics using time-series techniques on carbon stock data. For datasets limited to three key years (2001, 2011, 2021), the study analyzed trends by calculating changes and performing linear regression to estimate the change rate, testing its significance. The Mann–Kendall trend test was used to detect monotonic trends, a standard environmental method (Gilbert, 1987). Spatial assessment involved mapping carbon stock changes across the city using GIS, comparing maps from 2001, 2011, and 2021 to identify areas of carbon gain or loss, such as vegetation regrowth or deforestation.

The integrated temporal and spatial analysis provided a clear depiction of the carbon stock dynamics in Jinja City over the two decades. The results enabled the quantification of the net change in ecosystem carbon and helped characterize the nature of the change whether steady, abrupt, or variable over time. Additionally, interannual variability in NPP was considered in relation to climatic influences such as rainfall variability and extreme events like droughts, as well as anthropogenic land management practices. This analytical foundation set the stage for evaluating the relationship between urban expansion and carbon sequestration, which formed the basis for Objective 3.

### 3.7.3 Specific objective 3: Examination of the relationship between urban expansion and carbon sequestration in Jinja City

This objective aimed to assess the connection between urban expansion and carbon sequestration in Jinja City. Building on the findings from Objective 1 and Objective 2, we employed an integrated approach that combined statistical regression and spatial overlay techniques. A regression analysis was conducted to examine the statistical relationship between urban expansion and carbon sequestration. Spatial regression analysis was applied, with carbon stock as the dependent variable and urban area or expansion indices as independent variables. Spatial analysis further clarified this connection by overlaying urban expansion maps with carbon stock change maps for the same years using GIS tools(Hong et al., 2024). This spatial overlay showed that areas shifting from non-urban to urban experienced the greatest carbon stock declines. Zonal analysis was also used to compare the average carbon loss in newly urbanized zones versus those that remained vegetated.

To effectively communicate these findings, various visualizations were developed. Scatter plots illustrating urban area against carbon stock, with fitted regression lines, clearly demonstrated the negative trend. Maps showing spatial patterns of urban growth and related carbon losses offered intuitive evidence of the transformation occurring across Jinja City. These visual outputs complemented the quantitative results and enhanced understanding.

### 3.8 Software to be used

The software used in this research for data analysis includes QGIS 3.24 Tisler, RStudio Build 554 to perform supervised classification and post classification analysis, and Microsoft Excel to store coordinates from ground truthing data from the field

## CHAPTER FOUR RESULTS AND DISCUSSION

### 4.0. introduction

This chapter synthesizes the findings of this research with a focus on above-ground biomass, net primary productivity (NPP), and carbon sequestration results to evaluate how urban expansion has shaped Jinja City’s ecological carbon balance over 2001–2021. By integrating spatial-temporal patterns from biomass and productivity maps, this chapter articulates where and why vegetation has gained or lost carbon, linking urban expansion with deforestation, agricultural intensification, and vegetative regrowth. I examine the primary drivers of urban expansion and land cover change, assess their cumulative influence on Jinja’s ecosystem carbon stocks.

#### 4.1 Specific objective 1: Analyze the spatiotemporal patterns of urban expansion in Jinja City.

The classification results from the Landsat imagery over Jinja City demonstrate consistently high accuracy levels across three temporal years 2001, 2011, and 2021 indicating reliable land cover classification suitable for change detection and carbon sequestration analysis. Overall accuracies remained above 97%, with the 2001 Landsat EMT+ image achieving the highest accuracy at 97.20% and a Kappa statistic of 0.9613, followed closely by 2011 (97.043%, Kappa = 0.95) and 2021 (96.99%, Kappa = 0.9583). These high Kappa values (>0.95) indicate an almost perfect agreement between the classified maps and reference data (Landis & Koch, 1977), suggesting minimal classification error and strong reliability of the supervised random forest model used. The slight decline in accuracy over time may reflect increasing spectral confusion due to urban complexity and landscape fragmentation (Lu & Weng, 2007), particularly with expanding built-up areas and mixed-use land cover. Nevertheless, these metrics confirm the robustness of Landsat data combined with advanced classification techniques for long-term environmental monitoring and assessment of urban-induced changes in ecosystem services such as carbon storage (Foody, 2002; Congalton & Green, 2009).

*Table 3: Results of accuracy and kappa statistics for the classified maps*

Sensor	Date of acquisition	Overall accuracy	Kappa statistics
Landsat EMT+	27-11-2001	97.20%	0.9613
Landsat 8	12-12-2021	96.41%	0.9515
Landsat EMT+	9-12-2011	97.03%	0.9589

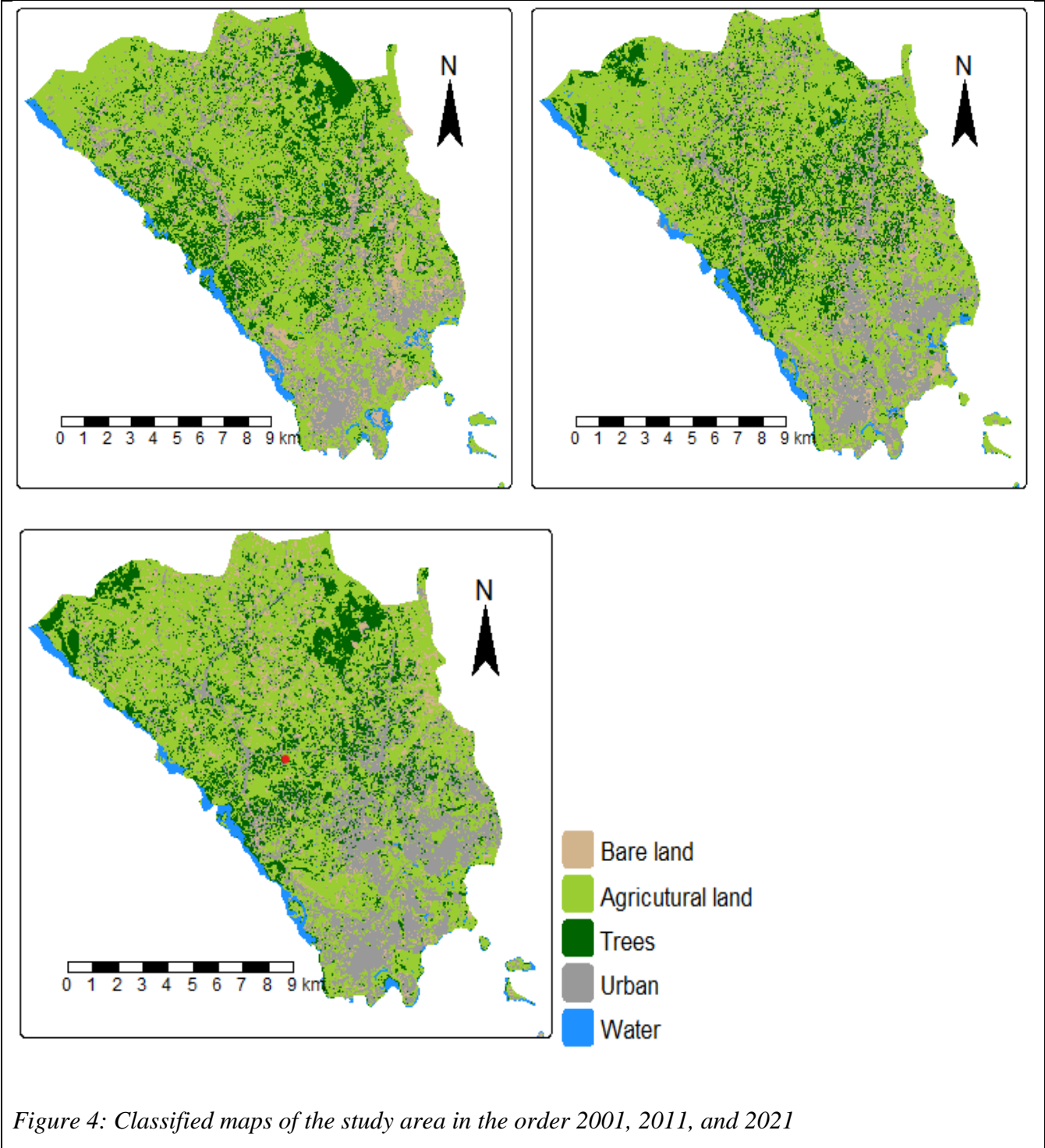


Figure 4: Classified maps of the study area in the order 2001, 2011, and 2021

#### 4.1.2 Temporal Trends in Urban Expansion

The analysis of land cover changes in Jinja City from 2001 to 2021 shows a clear and speeding-up trend of urban growth. Urban land cover grew from 2,727.71 hectares in 2001 to 4,104.80 hectares in 2021, a total increase of about 1,377.09 hectares or 50.5% over twenty years. This steady rise highlights the intensification of built-up areas caused by population growth, industrialization, and infrastructure investments. Notably, the pace of urban growth sped up in the second decade (2011–2021), with an annual increase of around 78.46 ha/year, compared to 59.25 ha/year in the first decade (2001–2011). This pattern reflects trends seen in other quickly growing secondary cities across sub-Saharan Africa, where urban sprawl is rapidly extending into peri-urban and natural areas.

As urban areas expanded, there were significant declines in other land cover types, especially tree cover, which decreased from 3,303.36 ha in 2001 to 2,808.60 ha in 2021 a reduction of about 15%. Bare land and water bodies also diminished, indicating that parts of the city's natural and undeveloped areas were converted into urban land. These changes show that Jinja's urban growth has come at the expense of carbon-rich and ecologically valuable areas. Although grass and crop lands declined only slightly (by 457.47 ha), their large initial extent (over 10,800 ha in 2001) suggests they may continue to face pressure if urban expansion remains unchecked. These land changes have important implications for carbon storage, biodiversity, and resilience to climate-related disasters (Bullock et al., 2021; Yao et al., 2019).

Indicate that urban expansion has been the most active and significant land cover change in Jinja City over the past 20 years. The conversion of vegetated or open areas into impervious urban surfaces results in decreased carbon storage, alters local climate, and increases ecological stress. This trend underscores the urgent need for strategic urban planning, the integration of green infrastructure, and land use policy reforms to balance development with environmental sustainability. Consistent with research from other African cities (Mugagga et al., 2017; Isabirye et al., 2016), the study highlights the importance of protecting remaining natural landscapes and increasing carbon sinks in urban areas to reduce the environmental impact of urban growth.

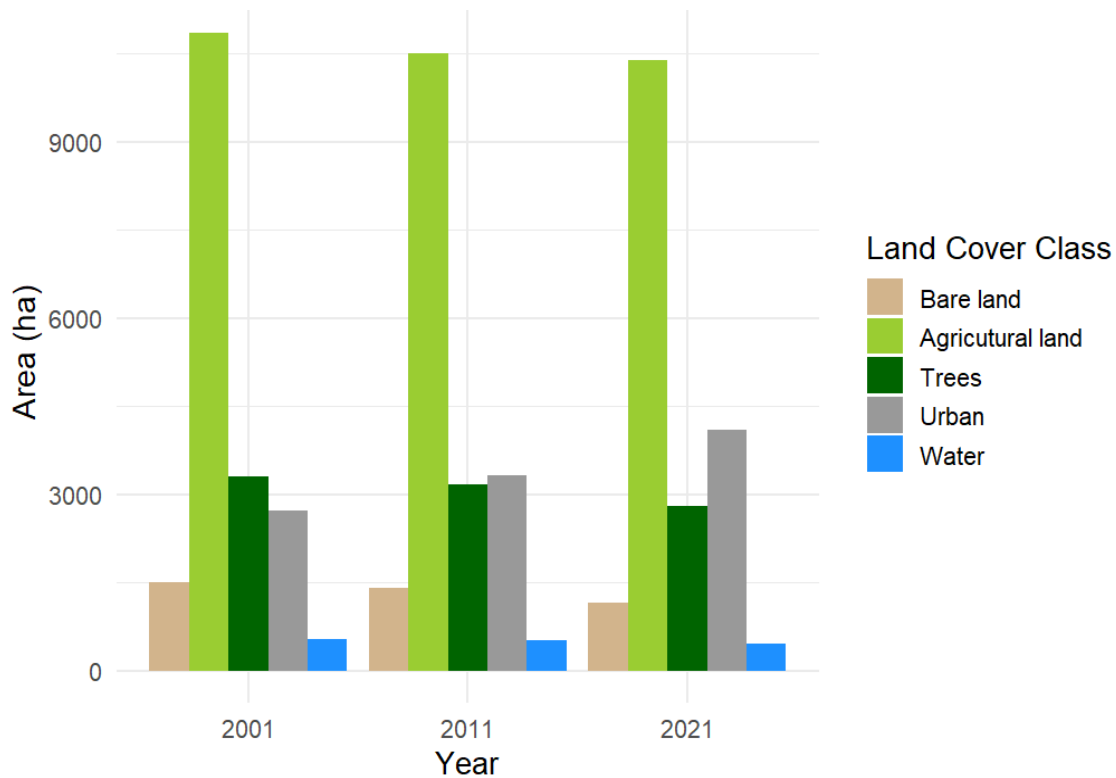
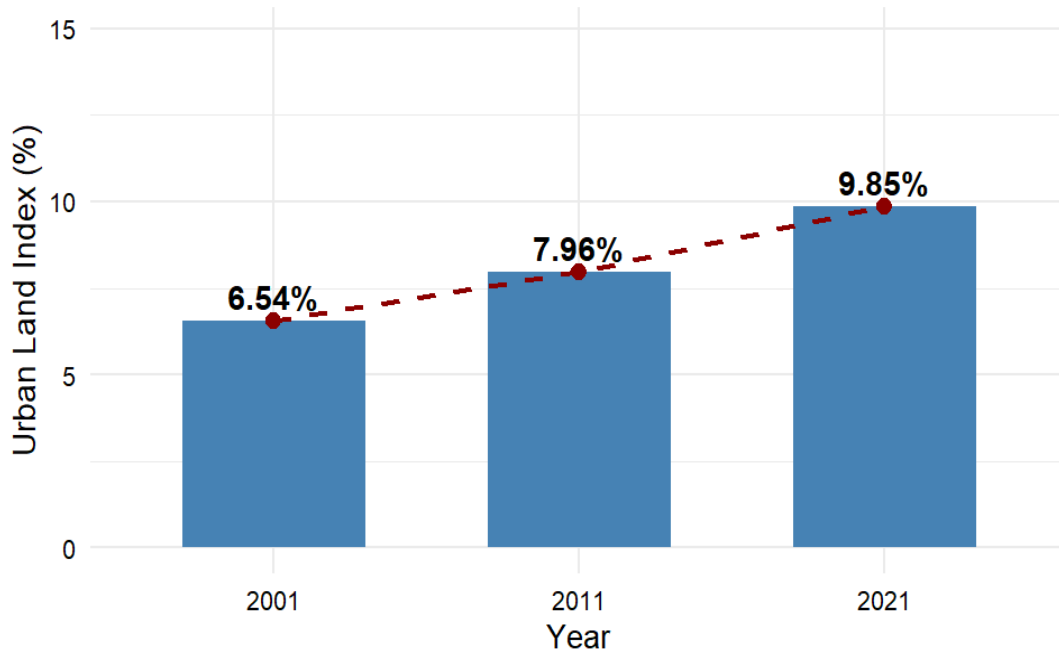


Figure 5 Bar graph showing land cover changes for the five land cover classes for years 2001, 2011, 2021

#### 4.1.2.1 Urban land index

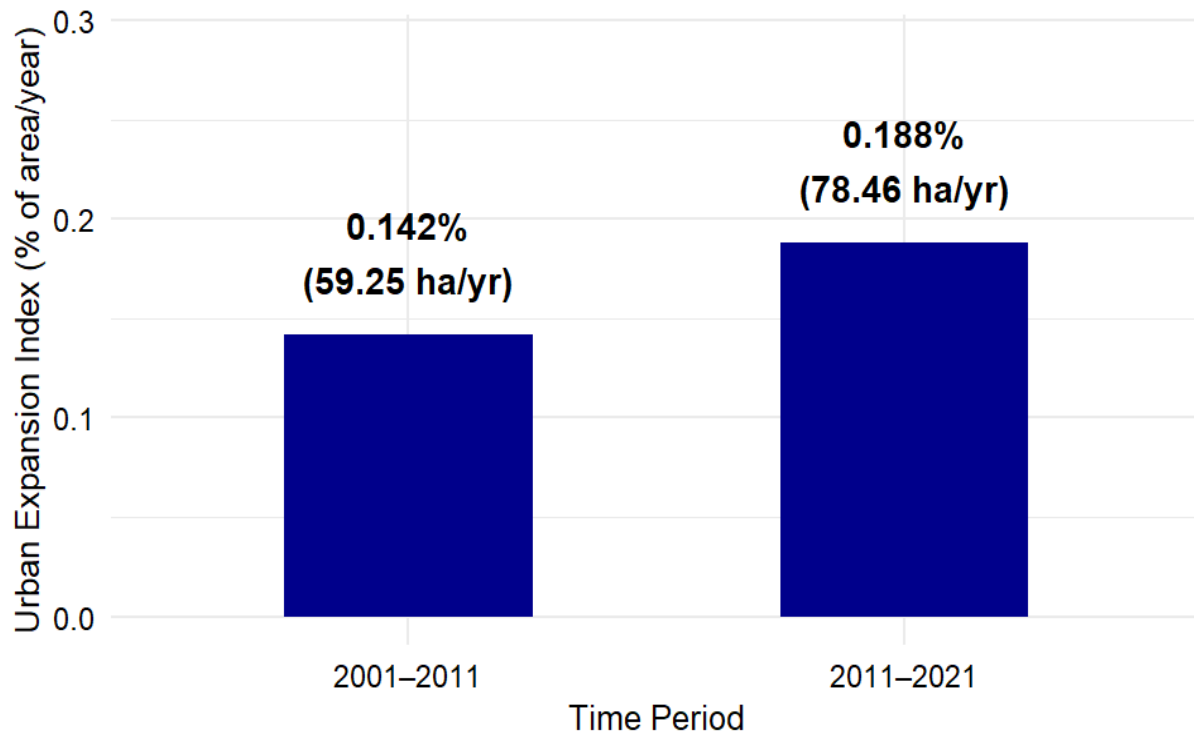
The Urban Land Index (ULI) measures urban development extent, showing steady growth in Jinja City from 2001 to 2021. ULI rose from 6.54% in 2001 to 7.96% in 2011, a 28% increase, driven by population, economic growth, and urban planning. From 2011 to 2021, it jumped from 7.96% to 9.85%, a 56% rise, indicating intensified urbanization, infrastructure expansion, and migration. This growth, especially along the Northern Corridor, impacts environment and land use policies, emphasizing the need for sustainable urban development.



*Figure 6 Urban Land Index (ULI) of Jinja city for the years 2001, 2011 and 2021*

#### *4.1.2.1 Urban expansion index*

The Urban Expansion Index (UEI) analysis for Jinja City reveals a notable acceleration in urban growth over the past twenty years. From 2001 to 2011, Jinja's urban area grew by about 0.142% annually (roughly 58 hectares per year), increasing to 0.188% (about 78 hectares) from 2011 to 2021. This doubling of the UEI indicates that urban expansion in the 2010s far outpaced that of the 2000s, aligning with broader urbanization trends in Uganda and sub-Saharan Africa. Uganda's urban population has been growing at nearly 6% annually, with secondary cities like Jinja expanding faster and reducing Kampala's dominance. This suggests Jinja has entered a phase of faster urbanization, becoming a significant urban center in eastern Uganda, reflecting a national shift toward more dispersed urban growth. The trend highlights Uganda's ongoing urban change and the global pattern of secondary cities driving development, with Jinja's growth in the 2010s surpassing the previous decade.



Jinja’s rapid growth highlights the importance of sustainable urban planning. Under SDG 11, cities must be inclusive, safe, resilient, and sustainable, with Target 11.3 promoting participatory planning. Uncontrolled expansion risks urban sprawl, inefficient land use, and environmental damage, including a 50% reduction in forest cover from 2010-2020. Service demands are evident: only 12% of residents in informal areas have access to safe piped water, and just 4% have sewerage. Growth could lead to slums, infrastructure shortages, and increased emissions resulting from longer commutes and congestion. Proactive, guided planning like UN-Habitat’s city extension approach can promote high-density, transit-oriented growth, conserving land and reducing costs. While rising UEI signals economic vitality, unplanned expansion creates challenges for urban governance and sustainability, risking degradation of natural assets and climate impacts. Addressing these issues is vital for Jinja to meet SDG 11’s goal of creating an inclusive, sustainable city, balancing development with environmental and social well-being.

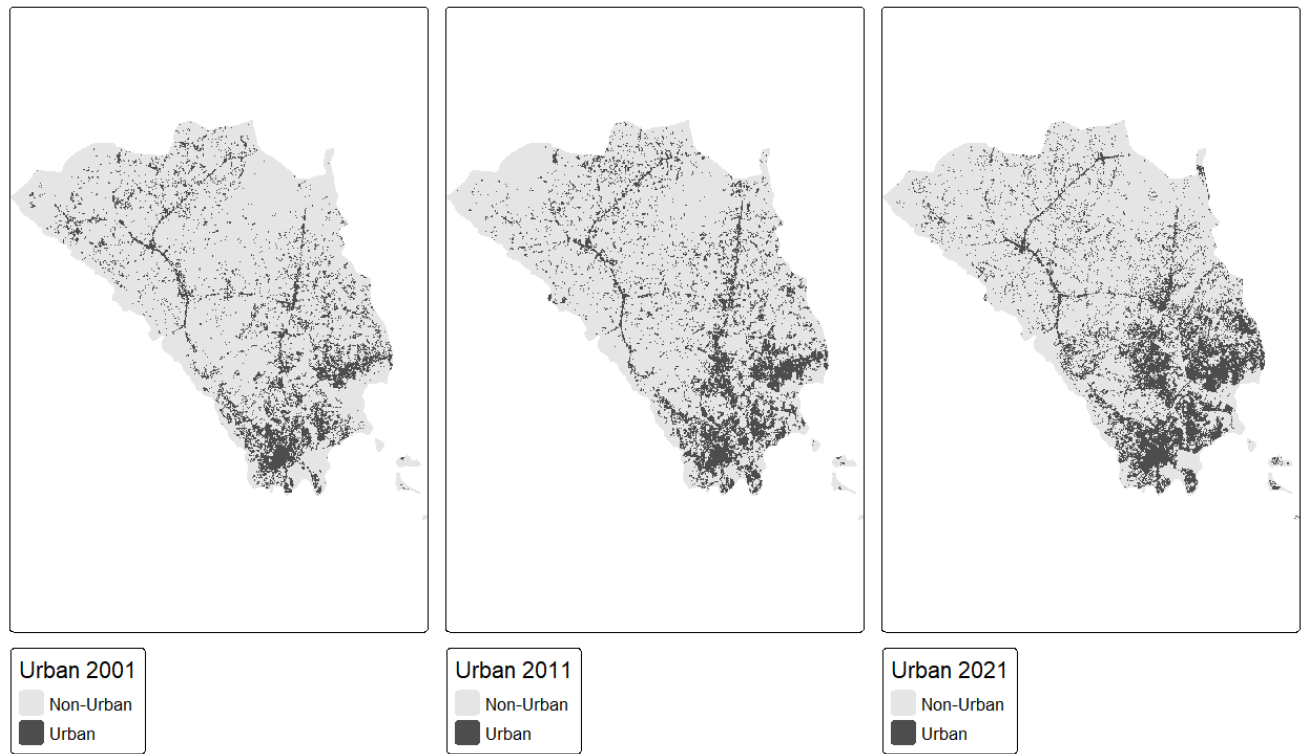
#### 4.1.3 Spatial Patterns of Urban Expansion in Jinja City (2001–2021)

When comparing the two sub-periods, distinct differences in growth patterns emerge. Between 2001 and 2011, urban expansion in Jinja was moderate and relatively controlled. Development mainly filled in the immediate edges of the city, such as along major roads just outside the old municipal boundaries and within undeveloped plots inside existing neighborhoods. During this decade, the urban footprint expanded outward in a compact manner. New housing and commercial buildings appeared near established neighborhoods, gradually enlarging the contiguous urban area. Most growth was connected to zones developed before 2001, indicating edge expansion around the city's outskirts.

From 2011 to 2021, the expansion became more noticeable and widespread. Urban growth in this later period not only continued along the city's edges but also extended further into outlying areas, effectively turning several formerly rural communities into urbanized zones. The maps from 2011–2021 show that settlements which were scattered or semi-rural and separate from the main city in 2001 became connected to Jinja's urban fabric by 2021. For instance, settlements along the Jinja–Iganga highway to the east and along the Jinja–Kamuli road to the north experienced substantial growth, transforming into continuous urban corridors. The growth pattern in the later decade included more leapfrog development and the absorption of satellite towns, resulting in a larger and more dispersed metropolitan area. The data support this increased activity: nearly 785 hectares were added as urban land from 2011 to 2021, compared to about 592 hectares in the previous decade. Therefore, although both periods contributed significantly to Jinja's expansion, the 2010s saw a broader scope of urbanization, likely driven by increased economic activity, infrastructure improvements, and the official incorporation of peripheral areas into the city. By 2020, Jinja's administrative boundary had expanded to cover 216 km<sup>2</sup> (up from about 61 km<sup>2</sup> previously), incorporating nearby settlements such as Mafubira and Bugembe into the city. This administrative change in 2020 reflected spatial realities in urban expansion that had been developing throughout the 2010s. Previously, outlying zones had effectively urbanized and become part of greater Jinja.

A key difference between the sub-periods is the type of land consumption. During the 2000s, expansion mainly took place on easily accessible land near the city, such as open tracts, former green spaces, or industrial brownfields at the outskirts, which were converted into built-up areas.

In contrast, the 2010s saw growth increasingly involving the conversion of active rural land like farmland and wetlands into urban spaces as the city expanded outward. A study on Jinja's land use changes showed that built-up areas grew at the highest rate, while green areas, swamps, and overall vegetation experienced the greatest loss. This suggests that the later growth phase came at a natural land cover cost, raising sustainability concerns.



*Figure 7 urban/built-up and cover type of Jinja city for the years 2001, 2011 and 2021*

#### 4.1.4 Ward-Level Variations in Urban Change

Spatial expansion in Jinja has been uneven across different parts of the city, with some wards experiencing much more growth than others. Map-based analysis of urban land change by ward from 2001 to 2021 shows clear geographic disparities in expansion. In particular, the northern and Northeastern outskirts of Jinja experienced the most significant increase in urbanized area, while the central city wards had relatively little room to grow further.

The ward-level change map in figure 9 shows Bugembe and Mafubira as the areas with the most significant increase in urban land from 2001 to 2021. Both are located outside the historic municipal core, with Bugembe to the east/northeast and Mafubira to the north of the city center. Each ward gained over 150 hectares of new urban land during these two decades, making them the top growth areas on the map. In 2001, Bugembe was a town council, and Mafubira was a sub-county; both were semi-urban or rural and separate from Jinja's main urban area. By 2021, they had transformed into urban neighborhoods and merged into the expanding city. The growth along the Jinja–Iganga highway in Bugembe is highlighted by the darkest shading, indicating the highest expansion. Mafubira, part of the Northern Division, also saw significant growth as areas like Namulesa shifted from rural villages to housing estates and peri-urban zones. The integration of Bugembe and Mafubira significantly contributes to Jinja's overall expansion, with local officials noting that peri-urban areas like Budondo, Mafubira, and Bugembe offered ample space for city growth when annexed, as documented on [jinjacity.go.ug](http://jinjacity.go.ug).

In contrast, many inner-city wards and established neighborhoods within the old municipal boundaries show minimal change in urban area. The Central Division (the historic city center and immediate surroundings) had little undeveloped land left by 2001, so its total urban extent did not grow much by 2021. Any growth in the central city was mainly vertical (through taller buildings) or infill development (using vacant lots) rather than outward expansion of the urban footprint. Wards in the southern part of Jinja's old municipality (such as Walukuba–Masese areas) show only moderate expansion on the map. These areas were partly built-up already and bordered Lake Victoria's shoreline and wetlands, which limited large-scale addition of new urban land. Some expansion did happen in Masese (for example, informal settlements spreading into wetlands along the lake) and in Walukuba (infill of previously open spaces in the old industrial housing estates), but the extent was much less than in the northern outskirts. Similarly, Mpumudde/Kimaka ward (west/northwest of the city center) experienced only modest growth; much of its land was already in use (including institutional land like the barracks and golf course) by 2001, so new urban development was gradual. A few other outer wards (e.g., Budondo area in the far north) remained largely rural with only small pockets of new urbanization, as shown by lighter shading on the map.

This ward-level variation highlights a common pattern in many growing cities: the quickest expansion occurs at the outskirts, especially along major transport routes, while the city center

expands more through densification than by increasing area. In Jinja’s case, the Northern Division (which includes Mafubira, Bugembe, and Budondo) has become the main growth area, whereas the Southern Division (the old municipality) experienced slower spatial expansion. Indeed, when Jinja became a city in 2020, Mafubira and Bugembe were explicitly identified as the newly added areas now forming the urban Northern Division, indicating they were previously outside the city but had significantly urbanized.

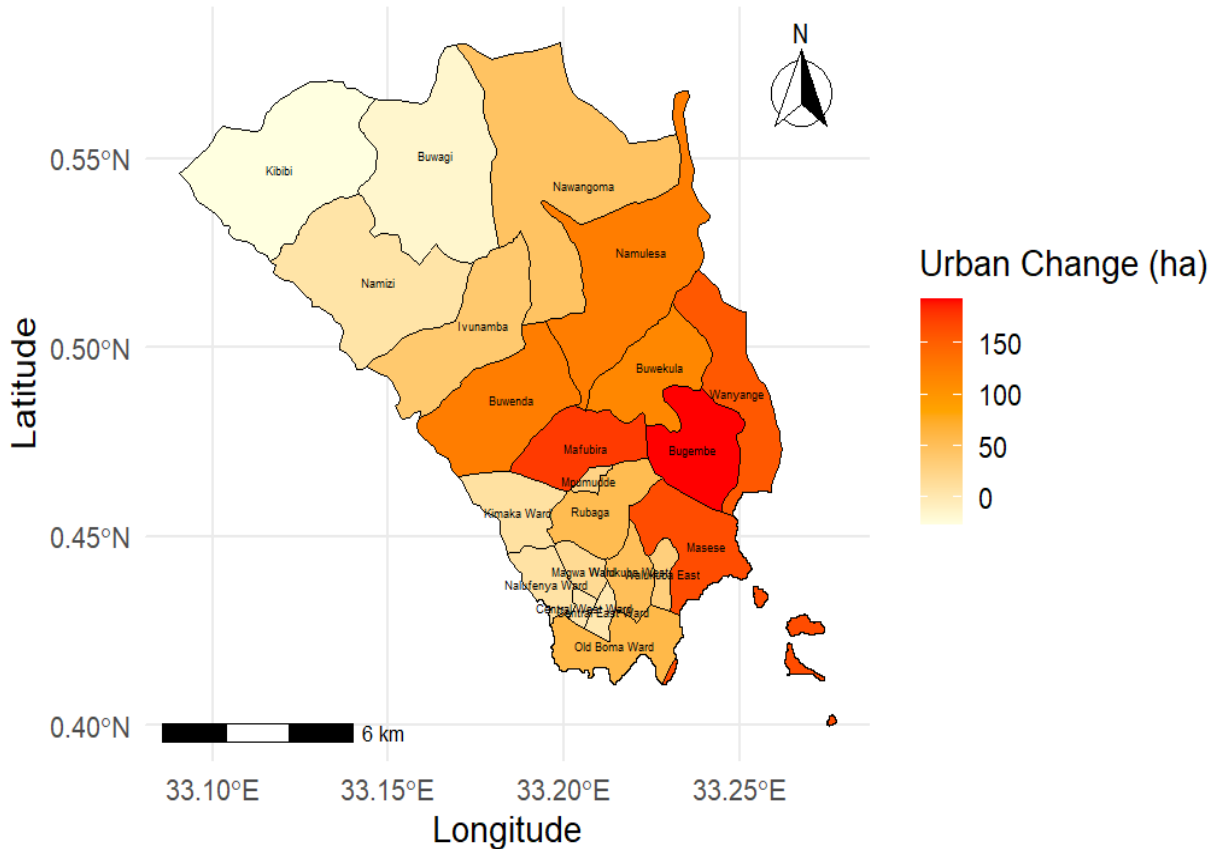


Figure 8 urban expansion intensity according to zones for a period of 20 years(2001-2021)

#### 4.1.5 Hotspots of Intense Urbanization

Certain parts of Jinja experienced especially rapid urban growth between 2001 and 2021, mainly because of their strategic location and socio-economic factors. Leading these areas are Bugembe (to the northeast) and Mafubira (to the north). We have seen their significant increase in urban land; here, we explore why these areas expanded so greatly and highlight other notable growth centers.

Bugembe's rapid growth stems from its strategic location along the Jinja–Iganga highway and proximity to Jinja's industrial zone. This transit route has attracted commerce and housing for workers, with ribbon development of shops, markets, and homes expanding outward. Historically affordable, land in Bugembe became appealing as central Jinja's land grew scarce and expensive. In the 2010s, extensive building extended Jinja's eastward, driven by investors, residents, and industrial facilities like Kakira sugar estate, which provide jobs. By 2021, urban development had merged Bugembe into Jinja, showing its integration into the city.

Mafubira's rapid growth was driven by transport routes and land availability. The Jinja–Kamuli road passes through, and in the past twenty years, this corridor has urbanized quickly. Small rural centers like Namulesa attracted new residents due to Jinja's expanding economy and high demand for affordable housing outside the city. People from Jinja and nearby districts migrated into these outskirts, supported by rural-to-urban movement. Mafubira's land, once mainly agricultural, was subdivided into residential plots as demand increased. Outside old municipal boundaries until 2020, land was less regulated and cheaper, encouraging development. By the late 2010s, large housing estates and informal settlements emerged, transforming fields into neighborhoods. Infrastructure improvements like road upgrades and utility extensions made Mafubira more urban, extending Jinja's growth northward.

Walukuba–Masese in Jinja's south saw modest growth, especially in pockets. Walukuba, originally an estate for industrial workers, became denser with housing, while some expansion occurred toward Masese near Lake Victoria. Masese grew as people moved into affordable lakefront housing, some of it informal and unplanned, encroaching wetlands. Growth was driven by proximity to industrial zones and cheap land, but expansion was limited by environmental constraints and industrial land use.

Mpumudde–Kimaka (Northwest): In the northwestern quadrant, around Mpumudde and Kimaka, growth was modest, but there were still some hotspots of development like the Kimaka area, which benefited from being near the new bridge (the Source of the Nile Bridge) and the Jinja army barracks, which perhaps encouraged some service and housing development nearby. Additionally, planned institutions such as universities or training schools in this area led to some construction. However, overall, this zone had fewer drivers compared to Bugembe/Mafubira, mainly because

large portions of land were occupied by government or institutional properties that were not available for private development.

## 4.2 Specific objective 2, Quantify the spatiotemporal trends in carbon stocks in Jinja city

### 4.2.1 Patterns in land cover change of trees and agriculture

From 2001 to 2021, Jinja City experienced significant land cover changes, especially in its forests and agricultural areas (forests/woodlands and grass & crops). Data shows that both categories shrank over the 20-year period due to urban expansion encroaching on green spaces. The proportion of land covered by trees dropped from about 15% in 2001 to 13% in 2021, while agricultural land decreased from around 50% to 48%. In actual area, tree cover declined by approximately 495 hectares, and farmland/grassland decreased by about 457 hectares. These changes indicate a gradual shift of natural and farming lands into other land uses, primarily built-up areas.

Between 2001 and 2011, tree cover declined by about 137.9 hectares (4.2%), indicating limited deforestation. Grass and crop areas shrank by 345.8 hectares (3.2%). Tree cover stayed stable (15.4% to 14.7%) while agricultural land slightly decreased (50.4% to 48.8%). Urban expansion mainly converted agricultural land, with fewer forest incursions. From 2011 to 2021, tree loss increased to 356.9 hectares (11.3%), reducing land cover from 14.7% to 13.1%. Grass and crop areas decreased by 111.7 hectares (1.1%), showing slower deforestation as urban growth encroached on forests, especially after accessible farmland was already converted. By 2021, forests and farms partly gave way to built-up areas, with deforestation impacts increasing.

### 4.2.2 Trends in net primary productivity

Over the 20-year period, NPP maps show a general increase in vegetation productivity around Jinja, despite some localized declines. From 2001 to 2021, many areas display higher green intensity in 2021 than in 2001, indicating increased carbon absorption by plants. This matches regional studies in East Africa, which show a significant rise in mean NPP, from about 700 gC/m<sup>2</sup>/yr in 2000 to approximately 928 gC/m<sup>2</sup>/yr in 2020. East Africa's average NPP increased by around 4.16 gC/m<sup>2</sup> annually, with Uganda experiencing above-average growth. The Jinja area

appears to follow this positive trend, possibly aided by better rainfall in certain years, CO<sub>2</sub> fertilization, and increased agricultural activity. Satellite data from the Lake Victoria region, such as the Mara Basin, also supports a widespread “greening” trend since the early 2000s, with NDVI increasing in about 75% of the area between 2001 and 2020, and only roughly 3.5% of regions, mostly savanna patches, showing browning. Overall, these vegetation growth trends suggest that climate and CO<sub>2</sub> effects have largely outweighed negative factors, leading to increased plant productivity in Jinja over the past two decades.

However, the changes over time are not universally positive. In figure 10, the maps from 2011 and 2021 reveal areas of declining NPP in comparison to 2001, particularly where urban or infrastructural land use has expanded. During the 2010s, Jinja City experienced considerable development, and such changes diminished local NPP by converting vegetated areas into built environments. In fact, regional data shows that from 2000 to 2020, approximately 29% of East Africa’s land area experienced decreasing NPP, while 71% saw increases. In Uganda, nearly all areas with significant changes demonstrated increasing productivity, yet a small percentage (around 3-4%) exhibited notable declines, particularly in central and eastern Uganda. Jinja, situated in eastern-central Uganda, likely hosts some of these decline hotspots due to urbanization. A recent local study indicated that Jinja’s forest cover fell by 50% between 2010 and 2020 amid rapid urban growth. This reduction in tree and vegetative cover during the late 2000s and 2010s would be reflected as lower NPP in 2021 for those newly developed areas when compared to 2001. In conclusion, the timeline presents a complex narrative: while overall productivity has grown over the past 20 years, swift urban expansion since 2010 has suppressed or reversed those local gains.

The magnitude of temporal changes is illustrated in the difference maps. From 2001 to 2021, the Jinja region saw net positive carbon sequestration (green areas), indicating higher annual NPP in 2021 than twenty years earlier. This suggests that vegetation is now fixing more carbon annually, benefiting carbon storage and ecosystem vigor. Agricultural and peri-urban zones show gains, possibly due to intensive cropping or vegetation recovery. In contrast, the city center and expanding suburbs display brown patches, indicating NPP drops as fields or forests converted to buildings and roads. The period 2001–2011 (left panel) shows minor changes (lighter colors), suggesting profound shifts occurred in 2011–2021 (right panel), coinciding with Jinja’s rapid

urban growth. This pattern underscores that recent urbanization has driven localized NPP decline against a background of regional productivity increase.

#### 4.2.3 Spatial trends in net primary Productivity

The NPP maps in figure 10 reveal spatial variations, showing stark contrasts between high and low productivity zones in the Jinja area, stemming from land cover and environmental gradients. Throughout all three years, specific zones consistently appear in dark green (indicating high NPP), while others show pale green or gray (indicating low NPP). High-NPP zones are likely characterized by dense or lush vegetation, such as agricultural plantations, wetlands, or forest patches. Jinja is surrounded by fertile agricultural lands, including sugarcane plantations and smallholder farms, alongside Lake Victoria and the Nile, where soil moisture is relatively abundant. These regions can achieve NPP levels around  $\sim 1200\text{--}1600\text{ gC/m}^2/\text{yr}$ , comparable to tropical forest productivity, provided there is adequate rainfall. Regionally, Uganda's most productive lands, primarily in the western and southern parts, exceed  $1500\text{ gC/m}^2/\text{yr}$  due to plentiful rainfall and biomass. Although Jinja is not the wettest part of Uganda, it enjoys a moderate tropical climate conducive to strong crop growth and lush vegetation. Therefore, the greenest areas depicted in the Jinja maps likely represent well-watered croplands or woodlots that sustained high productivity from 2001 to 2021.

Low-NPP zones on the maps correlate with sparse vegetation or bare surfaces, such as urban areas like streets and rooftops, which exhibit minimal carbon fixation. By 2021, Jinja's urban core and industrial regions remain low-productivity spots amid a greener rural backdrop, highlighting the shift from photosynthesizing plants to impermeable surfaces. Natural bare ground and water bodies (e.g., Lake Victoria, River Nile) also show near-zero NPP. Jinja's spatial pattern presents a "green belt" of higher NPP around the city periphery and river zones, enclosing a low-NPP urban center. This pattern is common in rapidly urbanizing areas: vegetation flourishes in undeveloped and moist habitats, while built areas and cleared land create "cold spots" of productivity. In Uganda, the distribution of NPP is more homogeneous compared to drier East African nations, as much of Uganda, including Jinja, comprises arable land with moderate productivity rather than extremes like deserts or dense rainforests. Still, Jinja exhibits a mosaic of lush fields and concrete expanses, influenced by factors such as land use, moisture, and vegetation type.

The drivers of spatial differences are clear. High productivity zones correspond to areas with favourable conditions for plant growth adequate rainfall, rich soils, and vegetation cover (crops, grasses, trees). For instance, low-lying areas near Lake Victoria often have higher soil moisture and longer growing seasons, boosting NPP. Similarly, intensive agriculture (like plantations) can yield high leaf area and biomass, generating strong NDVI and NPP signals. Low productivity zones arise where vegetation cover is minimal due to natural (rocky substrates, steep slopes) or human (urban paving, overgrazing) factors. In Jinja, human factors are significant: urban development and land degradation diminish vegetative cover. Regionally, built-up land shows the most widespread NPP declines among land use types. This aligns with Jinja’s map, where urban areas lag behind surrounding croplands in carbon uptake. Therefore, spatial heterogeneity in NPP correlates strongly with land cover patterns vegetated land leads to high NPP, while impervious or barren land is at the low end.

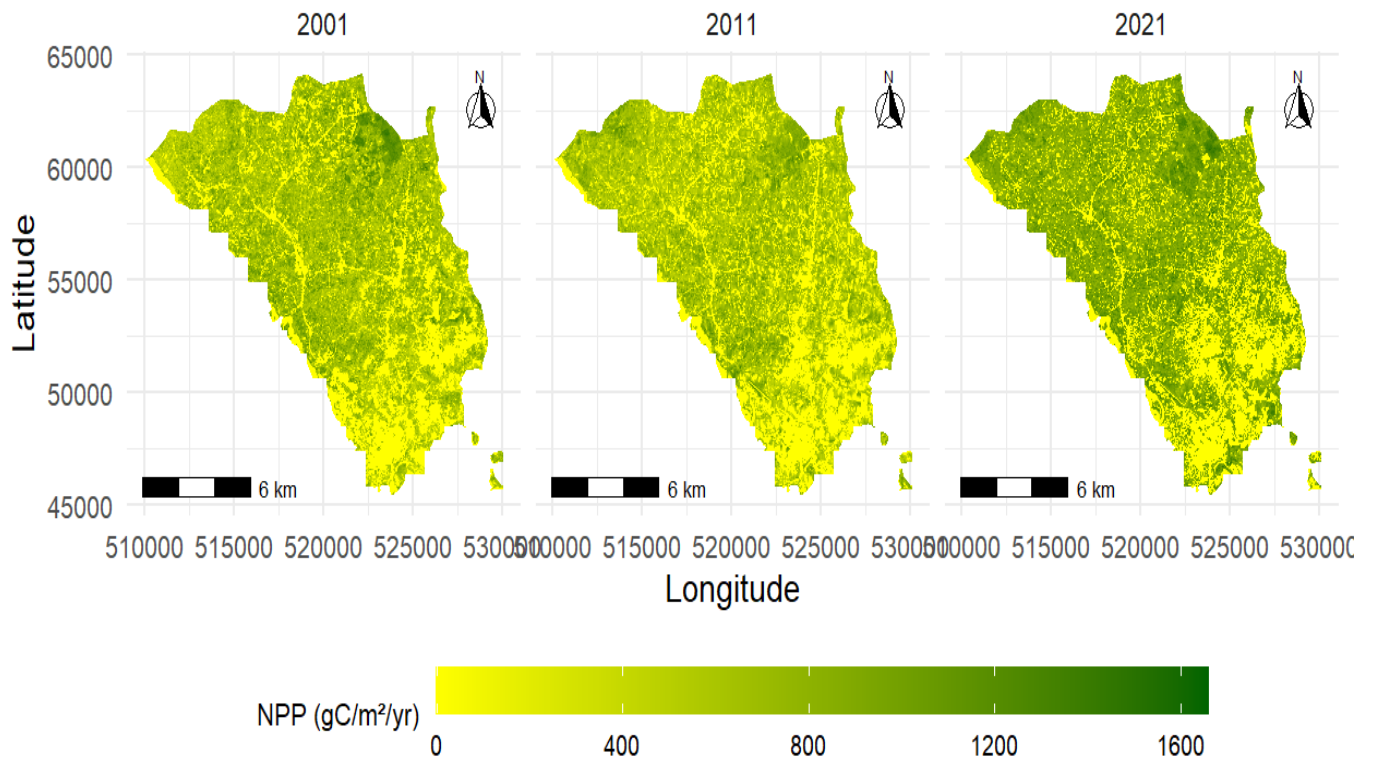


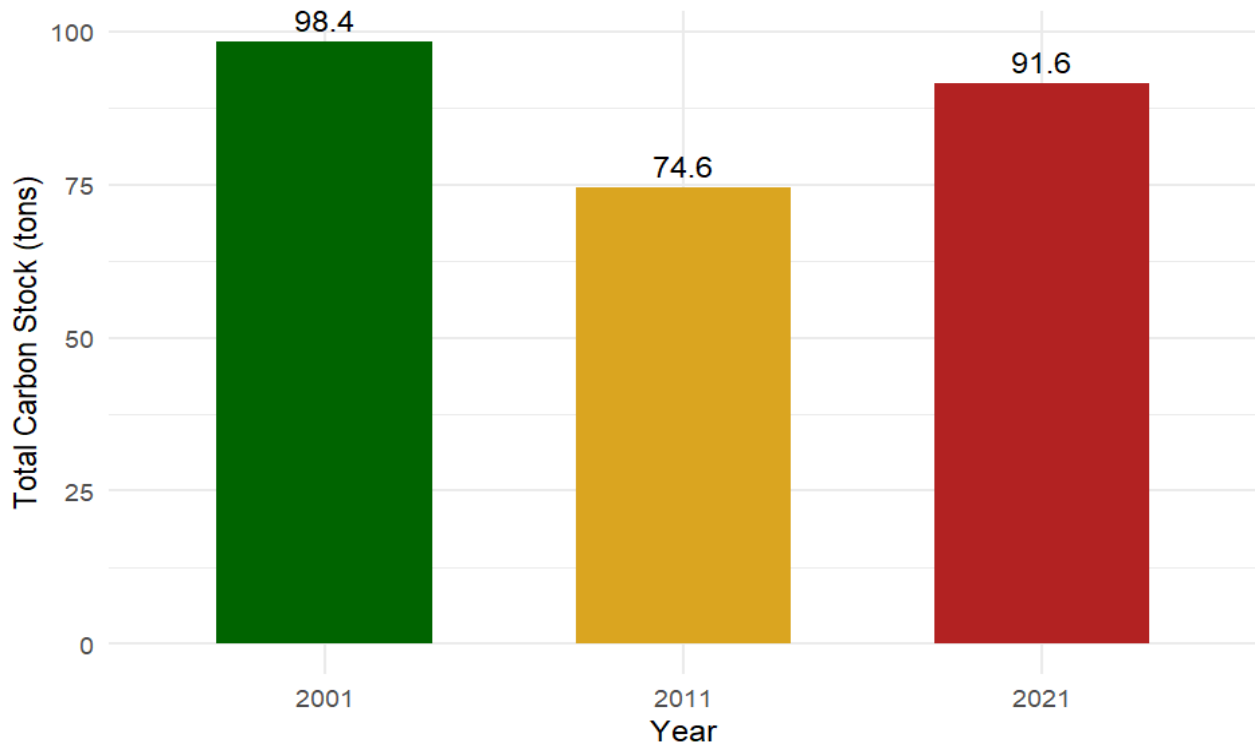
Figure 9 NPP map of study area

#### 4.2.3 Trends in carbon stocks

The analysis of total carbon stock in Jinja City from 2001 to 2021 showed noticeable fluctuations in the city's ability to sequester carbon over two decades. As depicted in the graph, the total carbon stock was estimated at 98.4 tons in 2001, the highest value recorded during the study period. By 2011, the total dropped to 74.6 tons, indicating a significant decline in vegetation cover and biomass carbon. However, by 2021, the total carbon stock partially rebounded to 91.6 tons, suggesting some vegetation regrowth or reforestation efforts in certain areas of the city. This trend indicates a general decrease in carbon stock in the first decade, followed by a moderate increase in the second, although overall levels stayed below the 2001 baseline.

The decline between 2001 and 2011 was mainly caused by rapid urban growth and the conversion of carbon-rich vegetation, such as trees and grasslands, into developed areas. During this time, urban development became more intense around the city center, major transportation routes, and suburban settlements, resulting in significant land-use changes. Consequently, vegetation that previously acted as a major carbon sink was lost, greatly decreasing the city's ability to absorb carbon. The sharp decline during this decade corresponds with the rapid population and infrastructure growth seen in Jinja City, especially within the former municipal limits. This period also coincided with increased industrialization and expansion of informal settlements, both of which led to deforestation and land degradation.

In contrast, the modest increase in total carbon stock from 2011 to 2021 may be attributed to urban greening efforts, reforestation initiatives, and natural vegetation regeneration in specific parts of the city. Although limited, the observed recovery shows that areas such as institutional grounds, riparian zones along the Nile River, and suburban green belts maintained or regained vegetation cover. However, this increase did not fully offset previous losses, suggesting that Jinja City's overall carbon sequestration capacity remained weakened. The ongoing urban sprawl, especially in the northern and eastern divisions, continued to strain peri-urban green spaces.



*Figure 10: Total carbon stocks for 2001, 2011, and 2021 of Jinja City*

The variation in carbon stocks in Jinja City from 2001 to 2021, as shown in Figure 12, clearly demonstrates a decline in carbon-rich landscapes over time and space, especially in tree-covered areas. In 2001, the distribution map shows widespread medium to high carbon densities (20 to 40 Mg C/ha) mainly in the northern and central regions of the city. These higher values reflect dense forests and well-vegetated zones that act as important carbon sinks and support ecosystem regulation. By 2011, visual evidence points to a substantial reduction in both the extent and density of carbon stocks. The central and southern areas, which once displayed moderate carbon levels, show a noticeable fading of green shades on the map indicating lower carbon densities. This change aligns with land cover shifts, particularly from trees and cropland to built-up areas. The decrease in green zones also indicates impacts like urban sprawl and infrastructure development, which contribute to biomass loss and carbon emissions (Velasco et al., 2016).

By 2021, the situation deteriorated further. The carbon map from 2021 indicates few areas with carbon levels above 30 Mg C/ha. Most of the city now features low carbon density (0–10 Mg C/ha), particularly in the core and peri-urban zones, where urban expansion was fastest. This

pattern corresponds with a total carbon decline of approximately 24.15% from 2001 to 2021. Notably, some of the last remaining vegetated areas are in the upper north-western zones, which still retain some carbon density and may be protected or less developed. These spatial patterns of carbon loss highlight ongoing ecosystem degradation caused by human activity. The reduction of green, carbon-rich patches hampers climate mitigation, worsens habitat quality, diminishes climate buffering, and lessens the city’s ecological resilience. The maps visually corroborate the data, emphasizing the urgent need for strategic land use planning, including restoring degraded areas and conserving remaining vegetated zones to prevent further carbon stock loss.

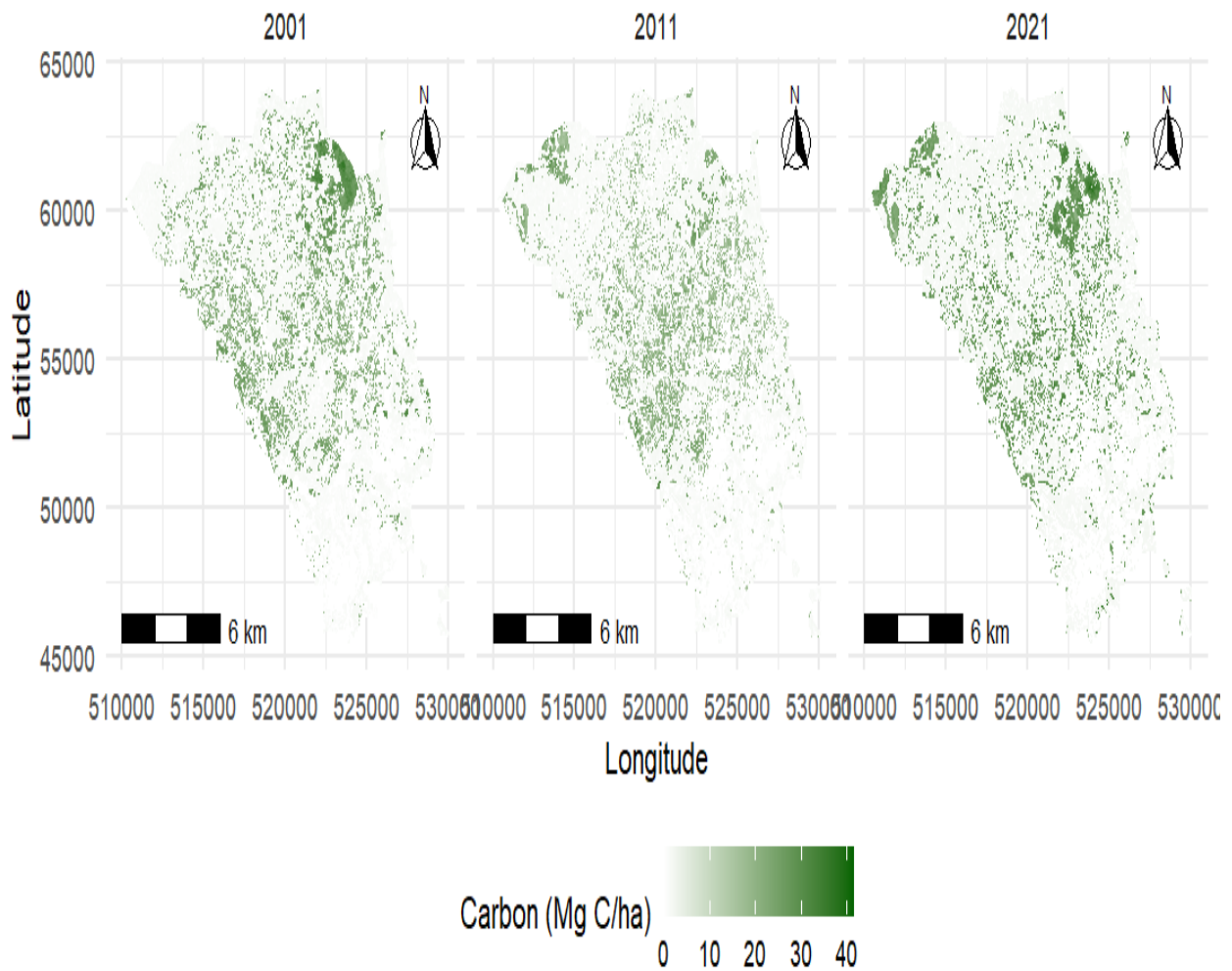


Figure 11: Map of carbon stocks of Jinja City

#### 4.2.4 Spatial and Temporal Patterns of Carbon Sequestration

Carbon sequestration (net carbon stock change) in Jinja City for 2001–2011 (left) and 2011–2021 (right), in Mg C/ha. Green areas indicate net carbon gains (sequestration), while brown/red areas show net carbon losses (degradation). The maps are based on LULC changes and carbon density values, with values calculated per hectare at [storage.googleapis.com](https://storage.googleapis.com). Each map uses the same color scale ( $\pm 20$  Mg C/ha) to facilitate direct comparison over the two decades.

Overall, the carbon sequestration maps for Jinja City show a varied spatial pattern of carbon gains and losses. Many parts of the landscape experienced only minor changes (light colors near zero), but there are clear hotspots of significant increase or decrease in carbon. Green shaded areas indicate locations where carbon stock increased (net sequestration) over the decade, while red shaded areas show where carbon stock declined (net carbon loss). These patterns reflect underlying land cover changes: areas that retain or gain vegetation (e.g., regrowing forests, tree plantations, or expanding green spaces) act as carbon sinks, while areas of vegetation clearance (e.g., deforestation or conversion to built-up land) become carbon sources. Mapping these changes is essential because it highlights the spatial distribution of ecosystem carbon dynamics, information that is crucial for land management and climate mitigation strategies.

During the 2001–2011 period, Jinja City experienced notable carbon losses concentrated in specific zones, with modest gains elsewhere. The north-western and northern outskirts of the city show the most prominent carbon degradation hotspots over this decade, visible as dark brown-red patches on the 2001–2011 map. In these regions, up to approximately 15–20 Mg C per hectare was lost, indicating significant vegetation loss. This likely results from deforestation or land clearing in previously carbon-rich areas, such as wooded or forested lands. Field observations suggest that Jinja's peripheral areas contained patches of natural forest and woodland; clearing these areas for agriculture, fuelwood harvesting, or urban expansion would release substantial amounts of carbon, consistent with observed losses. Conversely, carbon gains (green areas) during 2001–2011 were relatively limited. Several scattered patches on the map, such as west of the city center, show net gains of about 5–10 Mg C per hectare, possibly due to vegetation regrowth on fallow land or small-scale tree planting efforts. However, these sequestration gains were small and fragmented compared to the more continuous loss areas. Overall, the spatial pattern of the first decade

highlights dominant carbon loss in specific expanding zones of Jinja, with only isolated pockets of carbon gain.

During the 2011–2021 period, the pattern of carbon change shifted. The spatial distribution of changes in this later decade appears more mixed, with fewer large contiguous loss areas and a greater prevalence of green (gain) patches compared to the earlier period. Notably, the northern part of the city's territory, which experienced heavy losses in the previous decade, shows a different pattern in 2011–2021 some of these areas shifted to neutral (no further loss) or even slight carbon gains. A notable feature is a cluster of carbon sequestration gains in the northeastern and eastern regions (visible as dark green patches on the 2011–2021 map). These areas saw increases of about +10 to +20 Mg C/ha, indicating significant biomass accumulation. A reasonable interpretation is that certain lands underwent vegetation recovery or afforestation during this period such as abandoned agricultural fields reverting to bush, community tree-planting projects, or natural regrowth on previously cleared land. Meanwhile, the carbon losses in 2011–2021, marked in red, are still present but tend to be smaller and more dispersed. Small hotspots of loss (around 5–15 Mg C/ha) appear in patches around the western and southern edges of Jinja. These likely correspond to ongoing urban encroachment and infrastructure development in peri-urban zones, or the clearance of remaining small woodlots. However, the absence of large deep-red regions in 2011–2021 (unlike the previous decade) suggests that large-scale deforestation slowed or shifted. By 2011, much of the easily accessible forest near the city may have already been removed, leading to more incremental expansion, less dramatic per-hectare carbon loss, and in some areas, partial ecosystem recovery. Therefore, the map of the second decade reflects a more balanced mix of losses and gains, rather than the predominately loss-driven pattern seen in the 2000s.

#### 4.2.5 Areas of Highest Sequestration and Degradation

These figure 13 identify areas with the highest carbon gains (sequestration) and losses (degradation), often aligning with land use changes. The brightest green pixels (top sequestration hotspots) in Jinja's maps, mainly in the east and northeast during 2011–2021, gained about 15–20 Mg C/ha, possibly from vegetation recovery or reforestation. Some deforested lands may have regenerated or been reforested in the 2010s, causing significant carbon buildup. Such high

sequestration might result from community forestry or abandoned farmland allowing secondary forest regrowth. The bright green patches from 2011–2021, largely absent earlier, show an encouraging trend: parts of Jinja served as net carbon sinks, increasing local carbon storage and ecosystem services.

Dark red pixels indicate severe degradation, especially in northwest Jinja between 2001–2011, likely due to deforestation or urban expansion. Notable carbon losses also occurred along southern urban fringes, linked to rural-to-built-up land conversion. Ward analysis shows that eastern and southern areas like Mafubira, Budondo, and Mpumudde experienced significant urban growth, correlating with recurring carbon declines. When large land areas are urbanized, vegetation removal releases substantial carbon, causing red patches. Overall, high carbon loss areas are tied to deforestation driven by urban development and land-use changes.

In summary, the spatial analysis identifies two types of critical areas. Carbon hotspots of sequestration localized zones of recovering tree cover (notably in the 2011–2021 period in Jinja’s outskirts) that delivered the highest carbon gain and Carbon hotspots of loss of intensive land use change, particularly deforestation and urban expansion zones (more evident in 2001–2011), where most carbon was released (Indrawati et al., 2020). These findings align with general expectations for land-cover-driven carbon change forested lands, which store the most carbon, when lost cause the largest carbon emissions, whereas allowing vegetation to regrow can quickly rebuild carbon stocks mdpi.com. For example, tropical forest land can contain approximately ~124 Mg C/ha, while agricultural or developed lands hold only a fraction of that (often <15 Mg C/ha) (Qiu et al., 2023). Therefore, areas that changed from forest to non-forest in Jinja experienced a significant drop in carbon density, while areas that shifted from bare or low-biomass land to woody vegetation saw notable carbon gains.

#### 4.2.6 Comparison of Decadal Trends (2001–2011 vs 2011–2021)

A two-decade comparison reveals shifting carbon sequestration trends due to land use changes. From 2001–2011 in Jinja, widespread carbon loss was mainly from deforestation. The 2011–2021 period shows a more complex pattern with smaller gains and losses. In the first decade, Jinja’s net carbon was mostly negative, with emissions surpassing sequestration, linked to rapid land changes

and early 2000s deforestation when Uganda’s urban areas expanded. Uganda lost about 1.16 million hectares of tree cover from 2001–2024, releasing roughly 541 Mt of CO<sub>2</sub>, with Jinja’s small contribution reflecting the national trend of declining forest carbon stocks.

Between 2011 and 2021, Jinja’s carbon footprint improved, with map evidence of fewer large red areas and more green patches indicating decreased net carbon losses partly offset by gains. Factors include the depletion of accessible forests near Jinja by 2011, leading to smaller land clearances, increased awareness and conservation efforts possibly resulting in reforestation, and land use shifts like agroforestry or enrichment planting that boost carbon storage. These changes suggest a move towards more sustainable practices and a partial recovery in forest cover

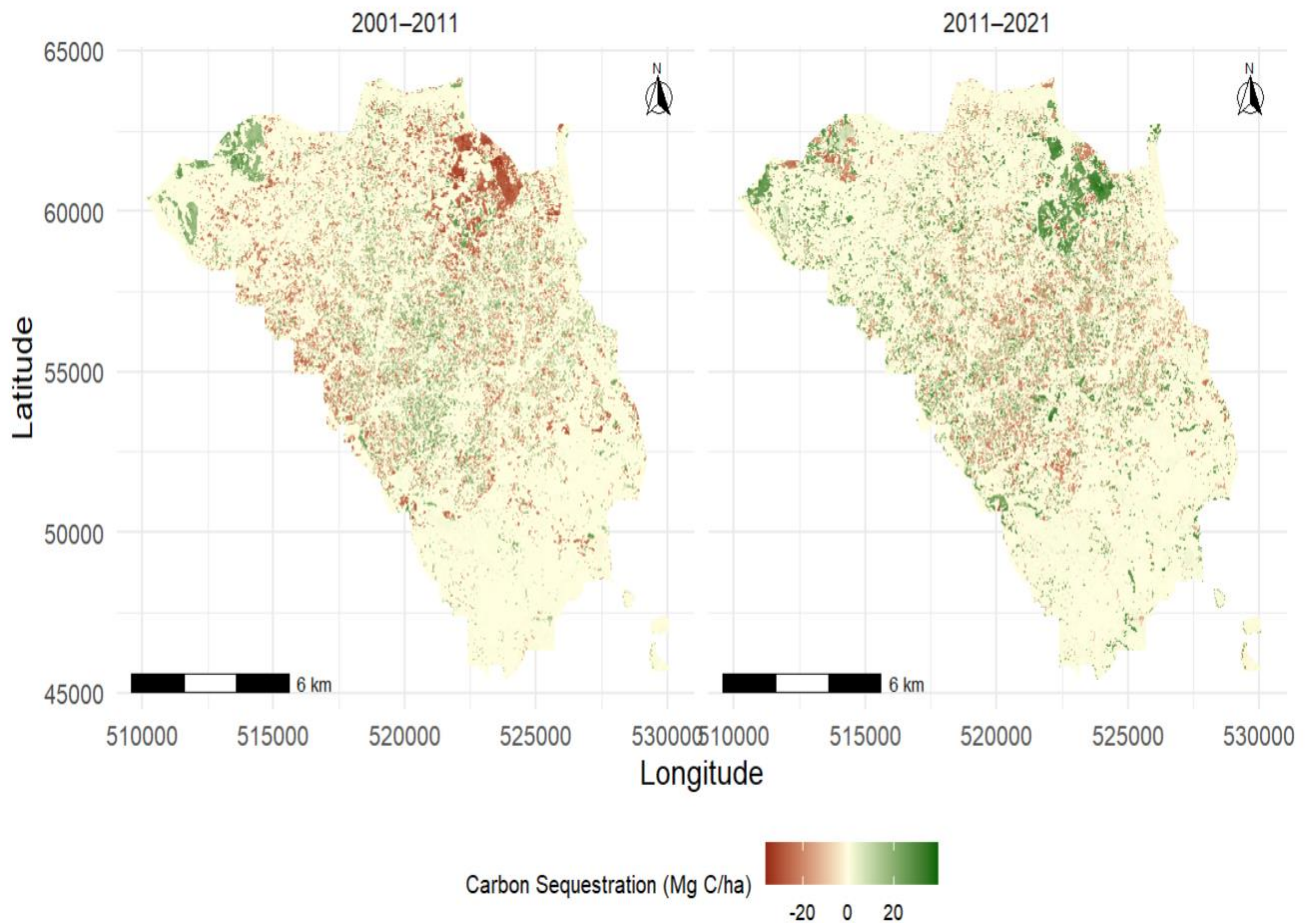


Figure 12 Carbon sequestration map of Jinja City

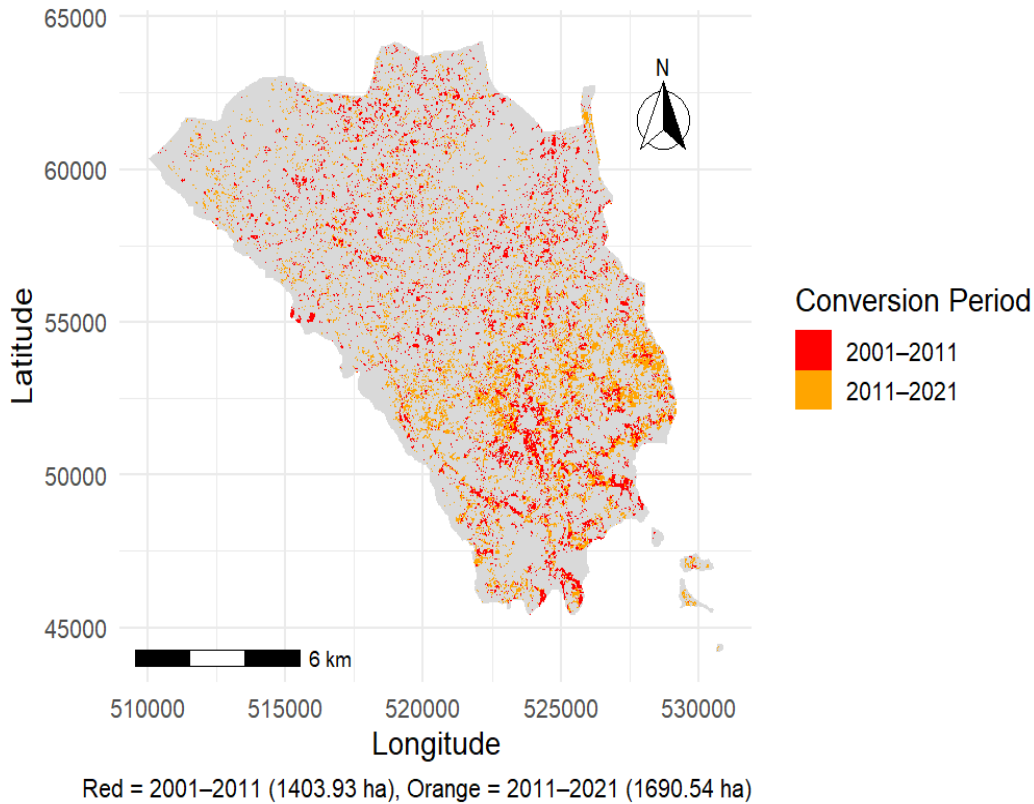
### 4.3 Specific objective 3: Relationship between urban expansion and carbon sequestration

#### 4.3.1 Statistical and spatial relationship

This study assessed the spatial and statistical relationship between urban expansion and carbon sequestration in Jinja City from 2001 to 2021. Using spatial overlay techniques and regression analysis, the study evaluated how the conversion of green space into urban land influenced changes in carbon stocks over three temporal segments: 2001–2011, 2011–2021. The spatial map in Figure 14 reveals the extent and distribution of green space (vegetation) converted to urban land over time. Red pixels represent areas that were urbanized between 2001 and 2011, while orange pixels indicate areas urbanized between 2011 and 2021. The results show a progressive urban sprawl from the central business district towards the peri-urban zones, with a total of 1403.93 hectares urbanized between 2001–2011 and 1690.54 hectares between 2011–2021. The expansion was particularly intense in the southern and eastern parts of the city.

This finding aligns with global trends where rapidly growing secondary cities in Sub-Saharan Africa are experiencing significant land-use changes driven by population pressure, economic development, and infrastructure expansion (Seto et al., 2012; Lwasa, 2010). Jinja's role as an industrial hub and transportation center has contributed to these expansion patterns. Carbon sequestration was estimated through modeled changes in carbon stock using CASA-based outputs. Two spatial datasets representing carbon change (2001–2011, 2011–2021) were analyzed. The results indicated that areas with increased urban expansion consistently saw reductions in carbon

stocks, reflecting a loss of vegetative biomass due to land conversion.



*Figure 13: Greenspace converted to urban area between 2001-2011 and 2011 and 2021*

#### 4.2 Spatial autocorrelation and regression

Moran's I analysis showed significant clustering in carbon stock change, especially from 2011–2021 ( $I=0.384$ ,  $p<0.001$ ), with a weaker pattern from 2011–2021 ( $I=0.122$ ,  $p=0.022$ ). This indicates that carbon loss areas are mainly urban zones and not randomly distributed. Using a Spatial Error Model (SEM) helped analyze the relationship between urban expansion and carbon change while addressing autocorrelation. Results align with other African cities, where short-term urban growth causes carbon loss, but long-term impacts depend on socioeconomic factors (Kabisch et al., 2017; Giannecchini et al., 2022). Studies with CASA models confirm that land conversion and built-up areas reduce carbon stocks.

*Table 4: Regression results showing the relationship between urban expansion and carbon sequestration*

Period	Urban Coef. (p)	Lambda (p)	Spatial Autocorrelation.	Conclusion
2001–2011	–23,760 (0.001)	–0.334 (0.314)	Weak	Urban expansion significantly reduced carbon
2011–2021	+2,735 (0.787)	0.542 (0.016)	Strong	Spatial effects matter, but no urban effect

The spatial regression analysis conducted to evaluate the relationship between urban expansion and carbon sequestration in Jinja City reveals different patterns over various periods. From 2001 to 2011, the urban expansion coefficient was statistically significant and negative (–23,760;  $p = 0.001$ ), indicating that increased urbanization greatly decreased carbon stocks. Specifically, for every hectare of new urban area, the carbon stock declined by approximately 25,494 grams of carbon (gC). This supports the hypothesis that urban development converts vegetated or forested land into impervious surfaces, resulting in a direct loss of above-ground biomass and a reduced capacity for carbon sequestration (Seto et al., 2012; IPCC, 2019). This finding suggests that transforming vegetated areas into built-up land results in a direct loss of biomass and soil carbon, consistent with findings from other rapidly urbanizing African cities (Seto et al., 2012; Lwasa, 2010). The spatial autocorrelation parameter (Lambda = –0.334;  $p = 0.314$ ) was not significant, and the model's fit (AIC) was nearly identical to that of the non-spatial linear model, indicating limited spatial dependence in the residuals during this period. Therefore, the results strongly suggest that urban expansion was a primary factor in the decline of carbon sequestration in the early years.

Between 2011 and 2021, the relationship shifted. The urban expansion coefficient was positive but statistically insignificant (+2,735;  $p = 0.787$ ), suggesting no clear effect of urban growth on carbon sequestration. Nonetheless, spatial dependence was significant ( $\text{Lambda} = 0.542$ ;  $p = 0.016$ ), and the spatial error model proved better than the linear model, indicating strong spatial autocorrelation in the data. These results imply that while urban expansion alone did not directly influence carbon changes, other spatial factors like reforestation, land management, or differences in carbon densities across regions may have had a more significant impact (Ziter, 2016; Miles & Kapos, 2008). It's also possible that recent urban growth involved less carbon-dense areas, leading to a subdued effect on carbon stocks despite land conversion.

Analysing the period from 2001 to 2021, the results reveal a small, statistically insignificant negative relationship between urban growth and carbon sequestration (urban coefficient =  $-3,006$ ;  $p = 0.453$ ). Although the spatial error coefficient was more pronounced ( $\lambda = -0.541$ ), it too was not significant, and the model fit ( $\text{AIC} = 706.07$ ) was only marginally better than the linear model. This pattern may suggest offsetting effects, where the substantial carbon loss due to expansion in the first decade was balanced by more neutral or less damaging urban growth patterns in the subsequent decade. Overall, these findings imply that the association between urban expansion and carbon sequestration varies over time and space, highlighting the importance of assessing urban environmental impacts within specific timeframes rather than across the entire period (Wu, 2014; Zhou et al., 2018).

## CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Conclusions

Specific objective 1: Analyze the spatial and temporal patterns of urban expansion in Jinja City between 2001 and 2021.

The study showed that Jinja's urban/built-up area almost doubled over the two decades, as shown by ULI and UEI, with the Northern Division, including Mafubira, Bugembe, and Budondo, being the main growth corridor, while the Southern Division expanded more slowly. From 2001 to 2011, rapid, unplanned urban sprawl into forests and green spaces. From 2011 to 2021, growth became more controlled and focused on infill development, indicating a shift to denser urban areas. These findings highlight diverse expansion patterns and suggest that later spatial planning helped slow land consumption.

Specific objective 2: Quantify the spatiotemporal trends in carbon sequestration and assess the relationship between carbon stock changes and urban expansion.

Urban green spaces serve a crucial role as carbon sinks in Jinja City, storing large quantities of carbon dioxide. Between 2001 and 2011, there was a notable decrease in carbon stocks due to the conversion of green spaces into built-up land. However, from 2011 to 2021, there was a slight increase in the NPP, AGB, and carbon stocks.

Specific objective 3: Determine the overall long-term impact of urban expansion on carbon sequestration in Jinja City.

From 2001 to 2011, the overall effect of urban expansion on carbon sequestration was statistically significant, indicating a negative impact. However, between 2011 and 2021, the environmental impact of urbanization lessened, indicated by a positive yet statistically insignificant urban coefficient in the spatial regression model.

## 5.2 Recommendations

Jinja City should limit sprawl and promote vertical growth to foster compact, low-carbon urban development over the next 1–5 years. It ought to redevelop 150 hectares of underused land in the Southern Division and boost density by 20% by 2030.

Conserve and protect at least 250 hectares of high-carbon green space and restore 100 hectares of wetlands and forests by 2030. An urban greening program planting 10,000 native trees annually can offset losses and increase carbon stocks.

Jinja City should embed carbon sequestration into urban planning within 5–8 years, linking urban growth to emissions. New proposals must include offset strategies, like planting one tree per 100 m<sup>2</sup> of impervious surface. Incorporate offsets or re-greening, with progress monitored through permit reviews and NDVI vegetation assessments to ensure a “no-net-loss” policy.

Establish an Urban Forestry and Greening Program (5–15 Years). The city should formalize efforts through a program that coordinates tree planting, community agroforestry, and green-space maintenance. Goals include increasing canopy cover by 15% by 2040 and creating five community agroforestry gardens by 2030. Success will be measured using satellite mapping, tree-survival surveys, and participation reports.

Introduce incentives to boost green, climate-resilient urban development over 5–15 years. The city should offer tax rebates, grants, and certification programs to encourage private and community involvement in maintaining vegetation, wetlands, or green roofs. Goals include engaging private developers in green building and agroforestry by 2035. Progress will be tracked via municipal registries, developer reports, and NDVI green cover mapping to evaluate private-sector engagement.

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