

**LAND USE/COVER CHANGE AND ITS IMPLICATIONS ON CARBON STOCKS IN
THE URBAN GREEN SPACES OF MBARARA CITY**

BY

**MUMPE GODFREY KABAKA
21/U/GMAG/14376/PE**

**A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH AND
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DECLARATION

I **MUMPE GODFREY KABAKA** declare that this dissertation report titled “**LAND USE/COVER CHANGE AND ITS IMPLICATIONS ON CARBON STOCKS IN THE URBAN GREEN SPACES OF MBARARA CITY**” is my original work and has never been submitted or presented to any university or institution of higher learning for any award.

Signed.....

Date.....

MUMPE GODFREY KABAKA

21/U/GMAG/14376/PE

APPROVAL

We the undersigned certify that this dissertation entitled “*LAND USE/COVER CHANGE AND ITS IMPLICATIONS ON CARBON STOCKS IN THE URBAN GREEN SPACES OF MBARARA CITY*” has been compiled under our guidance and supervision. It is now ready for submission to the Directorate of Research and Graduate Training with our approval.

Signed.....

Date.....

GABIRI GEOFFREY (PhD)

Signed.....

Date.....

TURYABANAWE G. LOY (PhD)

DEDICATION

This work is dedicated to my parents for their love and confidence in me.

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LIST OF ACRONYMS

AGC	Above Ground Carbon
AFOLU	Agriculture, Forestry and Other Land Uses
CA	Cellular Models
DBH	Diameter at Breast Height
GHG	Green House Gases
FAO	Food and Agricultural Organization
GIS	Geographical Information System
IPCC	Intergovernmental Panel on Climate Change
LULC	Land Use Land Cover
LULCC	Land Use Land Cover Change
MoFED	Ministry of Finance and Economic Development
MoLG	Ministry of Local Government
MWE	Ministry of Water and Environment
NEMA	National Environment Management Authority
NFA	National Forestry Authority
SOC	Soil Organic Carbon
UHI	Urban Heat Island
UBOS	Uganda Bureau of Statistics
USGS	United States Geologic Survey

ABSTRACT

Urban land use/cover change-driven effects on carbon stocks and emissions have become a critical concern for the attainment of sustainable urban development. Yet, the historical, current and future land use/cover changes and subsequent impact on carbon stocks in urban green spaces have not been well documented in the rapidly expanding cities in Sub-Saharan Africa. This study aimed to investigate the spatial-temporal land use/cover change and its impact on carbon stocks in urban green spaces in Mbarara city by; (i) examining the spatial-temporal changes in LULC between 2013 and 2023; (ii) quantifying current and historical carbon stocks in the different green spaces; and (iii) predicting LULCC and carbon stocks for 2043. To examine the LULCC, the study used satellite data from the USGS Earth Explorer for the series 2013, 2018 and 2023. Iso-Cluster and Maximum likelihood classification were used for image analysis in ArcGIS 10.8 version, and six LULC classes were identified; built-up areas, bushland, cropland, grassland, tree plantations and wetland. To determine the AGC, field measurements of tree DBH and height were taken and a destructive approach was used for the grass and herbaceous vegetation. Samples were taken to the laboratory for carbon content analysis. In addition, the LULC for 2043 was predicted using the CA-Markov model and future carbon stocks were computed following the IPCC guidelines. The findings revealed that built-up areas and tree plantations steadily increased in spatial extent by 11.8% and 0.3 % respectively while grassland, cropland, bushland and wetland decreased by 6.9, 4.2, 0.8 and 0.3% respectively by 2023. In addition, the built-up areas experienced the highest net gain while grassland experienced the highest net loss. Still, the total aboveground carbon stocks in green spaces were 73.40, 72.27 and 75.44 Gg for 2013, 2018 and 2023 respectively, the increase largely driven by an increase in the area under tree plantations. This study predicted LULCC, which shows, that by 2043, built-up area will cover 49.5% (21,1830 ha). As compared to the year 2023, built-up will increase by 33.9% while the area under grassland, bushland, cropland tree plantations and wetland will decline by 21.9, 7.7, 1.0, 1.4 and 1.9 % respectively. Consequently, the predicted LULCC are expected to cause a reduction in AGC storage of 38.55 Gg by 2043 resulting from the decrease in green spaces, especially tree plantations and grassland. It is evident that the explosion of built-up areas will persist at the expense of green spaces negatively affecting carbon storage. This highlights the need by city management to prioritize ecological protection and increase tree planting along all roads and public spaces to enhance carbon storage.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Urbanization is a critical driver of land use/cover change globally (Elmqvist et al., 2013; Haase et al., 2018), and environmental change (Leta & Demissie, 2021), leading to large-scale conversion of vegetation/green spaces to grey spaces, in turn releasing the carbon dioxide and other greenhouse gases (GHG) stored within the vegetation and soil into the atmosphere (Nero et al., 2020). As of 2021, approximately 56% of the global population were housed in urban areas, and his proportion is projected to rise to 68% by the mid-21st century, based on United Nations (UN) projections, reflecting an increment of 2.2 billion people largely happening in Africa and Asia (UN-Habitat, 2022). Equally, from the current three per cent, global urban land area is projected to triple between 2020 and 2030 (Zhang, 2016; UNDESA, 2021). Africa is the fastest urbanizing region (UN-Habitat, 2022) and cities are expanding at a rate of 500 Ha per annum while sacrificing agricultural and natural land cover (Nero et al., 2020), thus putting pressure on the ecosystem (Haase et al., 2018). These changes have been attributed to the unprecedented population growth caused by high birth rates and mass rural-to-urban migration (World Bank, 2021) exerting pressure on land resources like vegetation.

Urban green spaces are external places within the urban environment set aside for vegetation conservation to offer diverse ecosystem services (Abass et al., 2018). These spaces include urban forests and street trees, wetlands, public parks, and all permeable surfaces offer opportunities for both the above-and belowground carbon sinks, avoided emissions, and reduced energy use (IPCC, 2022; Wang et al., 2021; Sharma et al., 2021). In addition, they are a vital component in the reduction of stormwater runoff (IPCC, 2022a; Liu et al., 2014), urban heat island (UHI) effect and heat stress (Hunter et al., 2019), temperature mitigation (du Toit et al., 2018), enhancing urban resilience to climate change and the mitigation of disaster risks (Panagopoulos, 2019), improving air quality, mental and physical health, and the quality of life (IPCC, 2022a; WHO, 2016), and upgrading the townscape (Jim, 2013). Subsequently, urban green spaces are critical to realising the

United Nations Sustainable Development Goals (SDGs) 11 on sustainable cities and communities and 13 on climate action (Morton et al., 2017).

Despite the documented benefits, several studies in urban areas in Africa have reported the rapid conversion of green spaces into grey surfaces (Adegun et al., 2021; Aly & Dimitrijevic, 2022; Mensah, 2014; Otunga et al., 2014) such as residential, commercial, industrial and infrastructure establishments due to rapid population growth and high demand for land between competing land uses (Aly & Dimitrijevic, 2022; Mensah, 2014). Yet, urban expansion has been responsible for vegetation carbon loss (Velasco et al., 2016), which exposes urban areas to diverse environmental hazards (Agbelade & Onyekwelu, 2020) like elevated carbon dioxide concentration in the atmosphere, air pollution, and urban temperature elevation (Nero et al., 2020).

Land use and land cover change refers to the earth's biophysical characteristics modifications caused by anthropogenic and environmental influences (Hu et al., 2019). Ground-based and geospatial methods of analysis have been used to comprehend the spatiotemporal patterns and processes of urban areas and evaluate the role of green spaces in carbon capture and storage for climate regulation and other ecosystem services (Zhu et al., 2019; Wang et al., 2020). However, rapid urban expansion poses threats to urban vegetation leading to vegetation carbon loss and elevated atmospheric carbon dioxide burden and its related challenges (Haase et al., 2018; Velasco et al., 2016).

Carbon dioxide remains the principal anthropogenic gas, and its concentration in the atmosphere has notably increased by 31 per cent since the pre-industrial time, from roughly 277 parts per million (ppm) in 1750 to 409.85 ± 0.1 ppm in 2019 (Friedlingstein et al., 2020) which is attributed anthropogenic emissions from fuel use and land cover alterations, notably forest conversion (NEMA, 2007; UNFCCC, 2020). And yet, elevated atmospheric carbon dioxide burden amplifies surface temperature, climate change and urban heat island effect (UHIE) in the affected areas (Nero et al., 2020; UNFCCC, 2020), air pollution, alteration in rainfall patterns and intensity, leading to flooding, droughts and water scarcity, and multiple climate change-related illnesses (WHO, 2016). While urban areas make the most substantial contribution to greenhouse gas emissions estimated at 75% of global CO₂ emissions, land use changes (loss of vegetation, mostly deforestation) contribute nearly 23% of global Greenhouse gas (GHG) emissions (UNFCCC, 2020; IPCC, 2022).

Nevertheless, conservation and sustainable use of urban environments offer an opportunity for GHG emissions reductions (Haase et al., 2018; McPhearson et al., 2015). Evidence shows that increasing the carbon sequestration potential of terrestrial ecosystems is regarded as the most economically viable, effective and nature-based strategy for reducing atmospheric carbon dioxide concentration and climate change moderation (IPCC, 2022b; Wang et al., 2022).

Just like the rest of the developing countries, Uganda is experiencing a rapid urban growth rate of 5.3% per annum, and the Ministry responsible for regulating urban development (MoLHUD, 2017) projected that cities and towns will accommodate about 50 per cent of the total population in cities by mid-21st century from the current 20%. However, rapid urbanization characterized by uncontrolled physical expansion (urban sprawl) has interfered with environmentally sensitive areas such as green belts and wetlands (MoLHUD, 2017). The Uganda Vision 2040 and National Development Plan III, highlight urbanization as a key element in Uganda's development process (MOFPED, 2007), consequently, fifteen new cities have been created across the country, seven of which, including Mbarara city, became operational on 1st July 2020 (Nuwagaba, 2022). The elevation of municipalities to city status further worsens the environmental challenges of rapid urbanization by putting more pressure on land cover eventually causing the conversion of urban green spaces and fragile ecosystems like wetlands and urban forests/woodlots to built-up land use (Mbabazi & Atukunda, 2020). These changes affect sequestration rates and carbon fluxes in the vegetation and soil due to land use changes (Hendriks et al., 2020).

Mbarara City is experiencing rapid population growth of 5.0% per annum (UBOS, 2016), fast horizontal expansion and conversion of green areas to grey surfaces, ecosystem/biodiversity loss, and a significant portion of its urban forests, wetlands, and other green spaces have been degraded (Bwanika, 2016). Expansion of the built environment has led to the loss of unquantified urban green spaces and carbon stocks. This study therefore focused on analyzing the spatiotemporal land use/cover changes, current and historical carbon stocks in urban green spaces and prediction of future land use/cover changes and carbon stocks in Mbarara city.

1.2 Statement of the problem

Mbarara city is rapidly urbanizing at an alarming rate with the population growing at 5% annually (UBOS, 2016). This conversion of natural ecosystems to built-up spaces threatens the existence and functionality of urban green spaces hence leading to the degradation of the ecosystem and loss of unquantified carbon stocks and increased exposure to climate change effects such as urban heat islands, heat waves, flash floods and health complications (Kirago et al., 2022; Marselle et al., 2019). Despite the development guidelines, urban areas continue to grow haphazardly (Bwanika, 2016; MoLHUD, 2017). Previous studies in Uganda have predominantly examined land use/cover changes and carbon stocks in agroecosystems and natural forest environments (Birungi et al., 2023; Mugagga, 2015; Nakakaawa et al., 2011). However, there is a notable limitation in data on carbon stocks within different urban green spaces in Uganda's cities. Characterizing the effect of land cover transformations on carbon storage and fluxes in the urban environment is key to designing sustainable urban strategies. These insights are necessary to avoid the high costs associated with climate-related damages. Therefore, this study sought to bridge this knowledge gap by analyzing the land use/cover dynamics and carbon stocks within different green spaces in Mbarara City.

1.3 Study objectives and research questions

1.3.1 General objective

To investigate the spatial and temporal land use/cover dynamics and assess their impact on green space carbon stocks to inform sustainable urban planning and climate change mitigation for Mbarara City.

1.3.2 Specific objectives

The following specific objectives guided this study

1. To examine the spatial-temporal changes in land use/cover types between 2013 and 2023 in Mbarara city.
2. To quantify the current and historical carbon stocks in the different green spaces between 2013 and 2023 in Mbarara city.

3. To predict land use/cover changes and carbon stocks for the year 2043 for Mbarara city.

1.3.3 Research questions

1. What are the spatiotemporal changes in land use/cover types in Mbarara City between 2013 and 2023?
2. What are the current and historical carbon stocks of the different green spaces in Mbarara city?
3. What are the predicted land use/cover changes and carbon stocks in Mbarara City for 2043?

1.4 Justification of the study

Mbarara City is undergoing rapid urbanization leading to significant LULC changes (Bwanika, 2016; UBOS, 2016), which leads to loss of forest cover and other green spaces, and conversion of agricultural land to grey surfaces, in turn impacting the local and global carbon balance (Nero et al., 2020). Understanding the magnitude and impact of these changes is central to creating sustainable urban planning and management strategies. Land use/cover dynamics impact carbon stocks and emissions (Houghton et al., 2012; Xu et al., 2016), for instance, loss of vegetation cover can reduce the carbon sequestration capacity of the ecosystem and an increase in emissions. It is important to quantify carbon stocks and emissions dynamics and provide data that is valuable for effective greenhouse gas accounting and mitigation strategies.

Developing countries in tropical environments are often vulnerable to climate change hazards such as rising temperatures, heat waves, and extreme weather events (Mendoza-Ponce et al., 2018). Examining LULC changes and their effect on carbon dynamics helps in understanding the city's contribution to climate change or its mitigation. This study further contributes to the ongoing climate change agenda by highlighting the central role of cities in promoting sustainable growth as outlined in Uganda's Vision 2040 (MOFPED, 2007) and Sustainable Development Goals, particularly SDG 11 on Sustainable Cities and Communities and SDG 13 on Climate Action as entrenched in Global Agenda 2030.

1.5. Significance of the study

The findings of this study can be utilized by policymakers at the city level and other government agencies responsible for environmental protection like NEMA and NFA to design better policies aimed at the conservation of forests and wetlands, promoting sustainable urban growth and human well-being.

The findings provide up-to-date data on the rate and nature of LULC changes, carbon stocks in different green spaces and land use/cover change-related carbon emissions. This will help city planners to make evidence-based decisions that will ensure the achievement of urban growth and environmental sustainability. Such strategies may include green infrastructure development, zoning regulations and land use policies.

The findings will provide a foundation for further studies on urban land use/cover changes and green space management, carbon stocks and emissions dynamics and climate change, and sustainable urban development.

1.6 Scope of the Study

The study was conducted out in Mbarara City which covers a total area of 449.09 Km². The study covered the period between the years 2013 and 2023 and a projection for the year 2043. This time frame was considered for this study because Mbarara municipality and later Mbarara City was witnessing rapid and haphazard urban expansion triggered by the rapid population growth threatening the ecosystem and exposing the city to the perils of climate change (Bwanika, 2016; Nuwagaba, 2022; UBOS, 2016), as well as its elevation to city status in 2020 (Mbabazi & Atukunda, 2020). In addition, there was the availability of clear remotely sensed data of Landsat images (30 x 30 m) coverage for the area of study for the studied period which was a prerequisite for land use/cover analysis. Further, the study modelled land use/cover predictions for Mbarara city for 2043. The 20-year prediction was considered long enough to assess land use/cover changes in an urban environment. Regarding content, the study examined land use and land cover changes, current and historical carbon stocks and LULC and carbon stock projections in different green spaces in Mbarara city for the year 2043.

1.7 Conceptual framework

The conceptual framework in this study demonstrates links between land use land cover change and carbon stocks and emissions (Fig.1.1). The study conceptualized that urban land use expansion leads to an increase in built-up areas and the contraction of other land uses/covers including the urban green spaces. The increase in built-up areas and the decrease in urban green spaces leads to vegetation loss which is the main sink for the aboveground carbon, consequently reducing the carbon stocks while increasing the carbon emissions in and around the city. This exposes the residents to the repercussions of climate change which include urban heat island effect, global warming, heat waves and heat stress, air pollution, and health climate change-related illnesses.

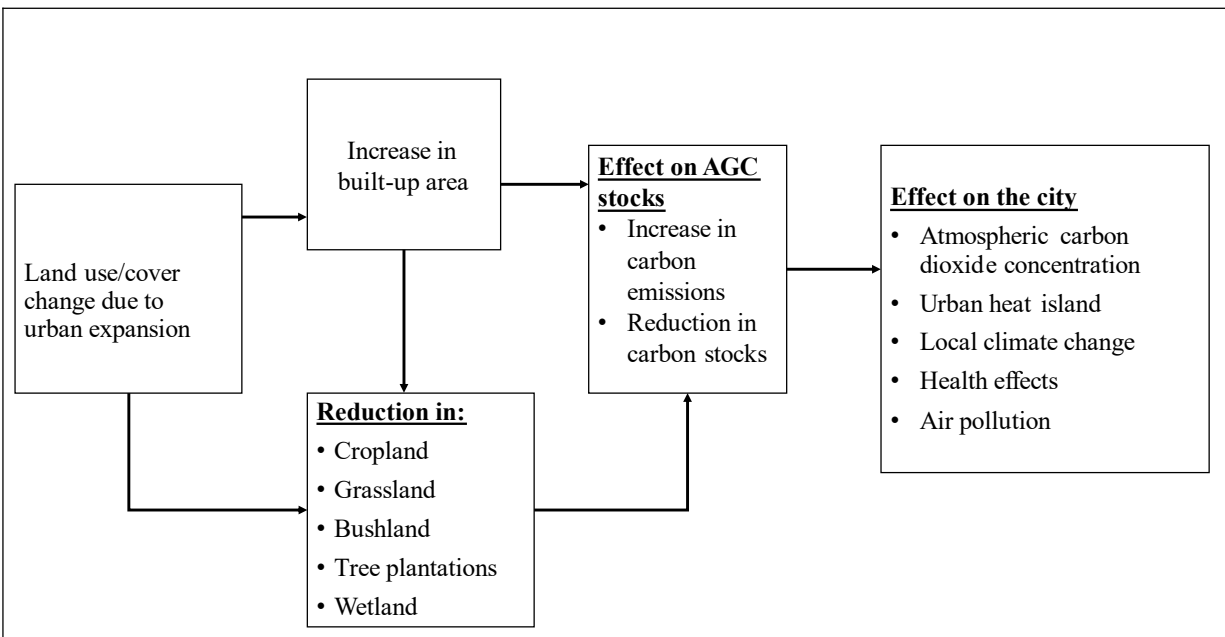


Figure 1. 1: Conceptual framework. Source: Author

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Land use/cover change refers to the alteration of the earth's biophysical characteristics caused by anthropogenic and environmental factors modelling land use/cover transitions and carbon stock predictions. The sources of literature included textbooks, journal articles, bulletins, government policy documents and other documents accessed electronically.

2.2 Spatial and temporal changes in urban land use and land cover types

Land cover is the natural appearance of the ground surface such as different vegetation types, bare land, or areas covered by water. Land use is the specific purpose that a particular piece of land has been assigned to by man, for example, settlement and farmland (Khamchiangta & Dhakal, 2020). Land cover change is the transformation of one type of land cover into another, such as the transition of a forest into grassland, cropland or built-up area (Houghton, et al., 2012). By 2016, approximately 60% of global land use changes were due to anthropogenic effects while 40% is related to indirect drivers like climate change (Song et al., 2018).

In 2021, the United Nations Department of Economic and Social Affairs (UNDESA) (World Bank, 2021) projected that the global urban population would reach 68 per cent, about 6.3 billion by 2050, while urban land area is projected to cover nine per cent of the global land area by 2030 (Zhang, 2016; World Bank, 2021)). Urban land expansion is expected to be higher in developing countries and lower in high-income countries (UN-Habitat, 2022). Asia and Africa are anticipated to have the fastest rates of urbanization (World Bank, 2021). Small and medium-sized cities and towns (accommodating below one million people) will continue to dominate in low-income countries impacting the realisation of the UN-SDGs (UN-Habitat, 2022). Yet, rapid urbanization is triggering huge problems, among which is environmental degradation (especially in developing countries) (Zhang, 2016)

The African continent has one of the fastest urban population growth rates growing from 395 in 2010 million and is expected to reach 1,339 million residents in 2050. This will trigger significant urban land expansion (Haase et al., 2018). Research across African cities reveals that urban areas are expanding at a rate of 500 ha per annum at the expense of natural land cover and farmed land (Komacek et al., 2017; Nero et al., 2020). Most of the urban growth is happening in small and medium towns (Haase et al., 2018), largely unplanned and unregulated, and therefore a major threat to the continent's sustainable development (Brandful et al., 2015). In 2017, only 20% of Uganda's total population constituted urban residents. However, projections indicate that by 2050, the share of urban inhabitants will reach approximately 50% based on the 5.2% annual growth rate (MoLHUD, 2017). Although the central region has been the dominant urban region, with Kampala as a primate city, the western and northern parts are also urbanizing rapidly (Tumwesigye et al., 2021)

A combination of geospatial data from remote sensing and the application of GIS tools are essential in analyzing LULC dynamics (Otunga et al., 2014). Careful attention should be given to the form and dynamics of urban land use and cover changes because of the varied impacts of specific urban land use changes. Besides the quantity of land transformed into urban land use, the original land use/cover and the main purpose, spread, distribution, and eventual cover features of the new urban land use are critical factors (Hoffmann, 2021).

Several studies on urban LULCC have highlighted fast growth in the coverage built-up areas and a substantial loss of green spaces and land use types related to green spaces such as agricultural land (Abass et al., 2018; Moniruzzaman et al., 2021). Densification of the inner city and the extension of urbanized areas along the rural-urban interface are responsible for the decline (Otunga et al., 2014). In the Bangkok Metropolitan Area, Thailand, LULC analysis revealed a 25% urban expansion while vegetation and water bodies decreased by 5% and 18% respectively from 1991 to 2016 (25 years) (Khamchiangta & Dhakal, 2020). Additionally, in Shanghai, it was revealed that whereas the suburbs, islands, and the entire city experienced the loss of green spaces for the period 1980-2015, the city centre registered an increase (Wu et al., 2019). In the Hefei region of China, urban expansion was responsible for the loss of vegetation and the reduction in ecological regulation (Yao et al., 2022). Similarly, a four-decade (1978-2018) analysis of Dhaka city in Bangladesh shows a radical increase of built-up areas amounting to 41.9% at the expense of

agricultural land, green spaces, and water bodies which declined by 14.6%, 16.0%, and 12.3% respectively. Interestingly, wetland area increased slightly by 1.4% (Moniruzzaman et al., 2021).

Similar findings have been reported in Africa. For instance, Eshetu et al. (2021) noted a reduction in green spaces in Addis Ababa between 2014 and 2018 because of land conversions, mainly cropland to housing and industrial land uses. Furthermore, in the Kumasi Metropolitan areas, grey spaces rose from 23.3% to 77.6%. The green space declined from 76.7% to 24.4% in three decades (1986-2016), and these changes were attributed to urban sprawl, rapid growth, and weak institutions (Abass et al., 2018). In the Bahir Dar city of Ethiopia, an analysis of LULCC using Landsat images series for 1991, 2002, 2011 and 2018 revealed fast growth of the grey spaces while agriculture and green spaces declined (Fitawok et al., 2020).

In Uganda, it was reported that land under built-up in Kampala more than doubled from 12,133 ha in 1995 to 25389 ha in 2016 (Id et al., 2021). As a result, the Kampala metropolitan area has witnessed a significant reduction in green spaces over time including forested areas, wetlands, and public parks that have been transformed into residential, industrial, and recreational grounds (World Bank, 2015; Aguilar, 2020). A similar study on land use/cover changes in Fort Portal between 1998 and 2016 (Wadembere and Kobugabe, 2017) reported a rapid loss of vegetation from 80.42% to 32.4% while the urbanized area and bare ground extended from 6.89% to 27.38% and 12.68% to 39.39% respectively, limiting environmental sustainability. In Mbarara, cropland and grassland areas have been transformed into built-up surfaces that experienced a 187% growth in 30 years (1984-2014) while the percentage of forest areas and swamps fluctuated (Bwanika, 2016). A population growth rate of 5% per annum for Mbarara City (UBOS, 2016) accelerates land use and land cover changes and environmental effects.

2.3 Carbon stocks in urban green spaces

Carbon stock is the total amount of carbon stored in an area or a sink (Padonou et al., 2016). During photosynthesis, vegetation sequesters atmospheric carbon dioxide, converts it into carbon and stores it in the biomass (Khaple et al., 2021) and in the soil as soil organic carbon (Woomer, 2004). In urban areas, most of the carbon stored in green spaces forms part of the external environment (Abass et al., 2018). Aly & Dimitrijevic (2022) define urban green spaces as “public

or private areas of cities that are covered by vegetation”. Such vegetated areas include wetlands, grasslands, and forests that provide considerable carbon pools which are important in climate mitigation (Haase et al., 2018; McPhearson et al., 2015). Notably, terrestrial ecosystems potentially fluctuate between net carbon sinks and sources depending on management dynamics (Jong et al., 2010; Temmink et al., 2022).

Green spaces store large quantities of carbon in vegetation and soil, for instance, in Kumasi, Ghana, aboveground trees in urban green spaces were reported to store about 1.934 million tons of carbon (211 C t/ha) (Nero et al., 2020). In Helsinki, Finland, Ariluoma et al. (2021) found that tree planting and biochar application in residential yards were instrumental in climate change mitigation because of the increased carbon storage potential. In addition, a forest-like design of urban green spaces was found to store more carbon in Leipzig, Germany unlike the park-like designs that are a source of carbon emissions through maintenance (Strohbach et al., 2012). Trees species, age, and stem density have been found to influence the quantities of carbon dioxide sequestered and stored in urban green spaces, with indigenous species performing better (Ngulani & Shackleton, 2022; Sharma et al., 2021; Wang et al., 2021).

Globally, the interplay among urban land use and land cover transformations and the carbon cycle in terrestrial ecosystems has attracted the attention of many scholars (Achmad, 2023; Elmqvist et al., 2013; Woome, et al., 2004; Yao et al., 2022). For instance, Yao et al. (2022) reported a link between the sharp increase in urbanised land in the Hefei province of China and the deterioration in carbon storage. Similarly, in a review of the impact of LULCC on carbon stocks in Aceh Besar, Indonesia, Achmad (2023), found a reduction in carbon stocks caused by significant changes in forestry and built-up classes, particularly deforestation. Another study by Erb & Vienna (2014) revealed that the alteration of forest to settled land, agriculture, and grassland was responsible for a 77% reduction in carbon stocks in terrestrial ecosystems in Austria; changes in species and stand age contributed to a 30% carbon stock reduction in forests.

Numerous studies on carbon stock dynamics under different ecosystems have reported similar results in Uganda. Mugagga (2015) investigated land use change and carbon stocks on Mount Elgon slopes and found that undisturbed forests contained higher soil organic carbon content (>45t/ha) than any other land use. Deforestation was noted to reduce the carbon stocks in the

region. A carbon stock inventory of Agoro-agu, a dry Afromontane forest (Birungi et al., 2023) revealed that the forest stored an estimated 606.7 mg ha⁻¹ mostly in the aboveground and belowground tree biomass and soil organic carbon. Litter, herbs, and grass stored the least amount of carbon. In eastern Uganda, Wambede et al. (2022) examined the carbon sequestration of fruit trees and reported variations in biomass and carbon stocks between different fruit tree species and management practices. For instance, mango trees held 74.57 +/- 14.95 t/ha compared to 13.52 +/- 1.25 t/ha of carbon in citrus trees. In an analysis of carbon stocks and emissions in farmlands in the Mount Elgon region (UNDP, 2017), carbon stock estimates of 0-307.1 t/ha were established, most of which was stored in the aboveground carbon pools which accounted for 60.7% and areas with higher forest/tree coverage had higher carbon stocks.

2.3.1 Land use/cover and carbon stocks

2.3.1.1 Forest ecosystem

In terrestrial ecosystems, forests are the main carbon sink (Gibbs et al., 2012); the key carbon stocks in the forest ecosystem are the living biomass of trees and understory vegetation, deadwood, litter and in the soil as soil organic carbon (SOC) (Amissah et al., 2023; Kothandaraman et al., 2020). Dense forests especially in the tropics have been found to store the bulk of carbon in the aboveground carbon pools (Houghton, et al., 2012) which is attributed to high average DBH and higher litter fall (Amissah et al., 2023). For instance, Kothandaraman et al. (2020) in a study involving a range of tropical forests in Western Ghats, India, found that variations existed in biomass and carbon content across the different types, but also a high average carbon density of 336.8 Mg C/ha, the bulk of which (65.5%) was stored in the live vegetation. In Brazil, a dry 30-year regenerating tropical forest stored 27.19 t C ha⁻¹, the greatest proportion (19.27 t ha⁻¹) was stored in the woody biomass (Andrade et al., 2016).

In Africa, studies have also shown a wide range of carbon densities in forest ecosystems. For instance, in the Hades catchment in Eastern Ethiopia, Toru & Kibret, (2019) found an average AGC of 116.46 t C ha⁻¹ in the natural forest with 81.5% stored in the above-ground biomass. Similarly, in Addis Ababa, trees in church compounds stored an average of 156 ± 92 t ha⁻¹, largely influenced by tree species and the age of the church (Yilma & Derero, 2020). On the other hand,

in the Agoro-agu forest in northern Uganda, AGC was 409 Mg ha⁻¹. Such wide variations in the aboveground carbon stocks have been attributed to the forest type, species composition, altitude, climatic and edaphic factors (Amissah et al., 2023; Toru & Kibret, 2019).

2.3.1.2 Wetlands

Wetlands are natural or artificial areas that are permanently or seasonally water-logged. They include marshes, swamps, bogs, fens, peatlands and mangroves (Bansal et al., 2023). In Uganda, the main wetland types are marshes, swamps and bogs (Wetlands Atlas, 2016). The wetland ecosystem plays a critical role in climate change by influencing the carbon cycle. Wetlands extract atmospheric carbon dioxide and store it as carbon in plants, the soil as SOC and in water as dissolved organic carbon (DOC) for long periods or emit carbon as carbon dioxide or methane (CH₄) (Bansal et al., 2023). Wetlands, which cover only 3 to 8% of the global land surface and 11% in Uganda, have a disproportionate effect on the global carbon cycle (Friedlingstein et al., 2020; Wetlands Atlas, 2016). Despite their small area coverage, wetlands store above 20% of worldwide organic ecosystem carbon (Temmink et al., 2022). Peatlands (boreal, temperate, and tropical aggregated) possess the highest carbon density per unit area (Temmink et al., 2022). An analysis of carbon sequestration potential reveals that wetlands have the highest carbon per unit area in comparison with forests because the majority of the carbon is stored as soil organic carbon (Temmink et al., 2022).

Carbon stocks in wetlands are highly prone to anthropogenic disturbances involving land use changes that include drainage, agriculture, urbanization, restoration construction and human-induced natural factors such as rainfall pattern changes and amounts and global warming (Bansal et al., 2023). Therefore, wetlands can be both a carbon sink or source depending on management practices making their conservation rather than restoration critical, Taillardat et al. (2020).

2.3.1.3 Bushland

Bushland vegetation is a mixture of bush, scrub, and thicket growing together as a unit usually not growing beyond a mean height of four meters (NFA, 2009). Also known as shrubs, the vegetation in bushland may be categorized as closed such as bushland thicket, open and very open occurring naturally as a climax or resulting from degraded forests or woodlands. Bushland vegetation store

carbon in their aboveground biomass, for instance, a study on carbon stock density across vegetation type in the West National Park in Burkina Faso (Dimobe et al., 2019) revealed an average of $2.9 \pm 0.4 \text{ Mg ha}^{-1}$ in shrub savanna while in the miombo woodland of Mozambique, the herbaceous vegetation (bushland) stored $0.02 \text{ Mg C ha}^{-1}$ (Ribeiro et al., 2013).

2.3.1.4 Grasslands

Grasslands are ecosystems characterized by a relatively high cover of grasses and other graminoid vegetation with limited or no shrub and tree cover (Monson, 2014). Grassland ecosystem covers 40.5 % of the terrestrial area including the meadows, prairies, rangeland, savannas, steppes, or tundra existing in different continents often known as natural grasslands (Monson, 2014; Sanderson et al., 2015). Grasslands offer multiple ecosystem services among which is carbon storage mainly in the soil because of their high root-to-shoot ratio. However, the grassland ecosystem is threatened globally by land use changes especially cultivation and urbanization (Monson, 2014). Therefore conversion of grassland to other land uses releases the carbon stored in the biomass and the soil (Ghosh & Mahanta, 2014).

Different grassland systems store varying amounts of carbon (Ghosh & Mahanta, 2014). In Yunnan province, grassland took 19% of the total ecosystem carbon stock while forest land took 68% (Li et al., 2022). In the Loess Plateau of China, grassland aboveground carbon density extended from 0.04 to 0.33 kg C m⁻², (Wang et al., 2018). On the Qinghai Plateau of China, aboveground grassland carbon concentration was from 0.04 to 2.80 kg C m⁻² (Liu et al., 2016). In Muscat, a study by Amoatey & Sulaiman (2020) found that turf grass stored $0.24\text{-}0.604 \pm 0.09 \text{ kg C m}^{-2}$ in aboveground carbon. A similar study in the Agor-agu tropical dry forest ecosystem in northern Uganda established the grassland aboveground carbon density of 0.24 mg ha^{-1} (Birungi et al., 2023).

2.3.2 Methods for estimating carbon stocks in biomass

Three main methods have been raised for measuring biomass and carbon in an ecosystem or landscape: ground-based or field measurements; remote sensing-GIS; and modelling (Gibbs et al., 2012; Padonou et al., 2016). Ground-based methods involve taking inventory of the forest with direct methods that involve destructive methods and indirect methods that rely on measurement of

forest types, stand age, stand density, stand volume (Sun & Liu, 2020), tree height and diameter at breast height (DBH) which are converted into biomass using allometric equations (Hasdiana, 2018). Destructive methods involve cutting the vegetation, drying it and measuring the dry mass which is then converted into carbon (Gibbs et al., 2012). However, in forest ecosystems, this approach is hectic, destructive, time-consuming, costly and generally impractical for large-scale analyses. Thus, indirect methods are the most used because of their ease of application and cost-effectiveness (Gibbs et al., 2012). Allometric equations have been developed for specific biomes (Gibbs et al., 2012; Houghton, 1999; Houghton et al., 2012) and area-specific equations (Daba et al., 2019; Forest et al., 2018; Tashi et al., 2017). In tropical forests, (Chave et al., 2014) application of generic allometric equations is recommended because they have been developed based on a large sample of trees analysed by destructive means. These equations utilize tree height, diameter at breast height (DBH) and wood-specific density to determine biomass because 95% of the biomass is accounted for by DBH (Houghton et al., 2012). In grassland and herbaceous vegetation, field measurements involving destructive methods have been widely used (Birungi et al., 2023).

On the other hand, the combination of remote sensing instruments and ground-based data improves their accuracy (Gibbs et al., 2012). These instruments include optical satellite sensors, such as Landsat, Advanced Very High-Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS), very high-resolution aerial imagery from airborne sensors and LiDAR (Light detection and ranging) which measure tree height and crown or diameter, and use them to compute biomass and carbon using allometry (Gibbs et al., 2012; Sun & Liu, 2020). Lastly, the process-based estimation or modelling method is typically divided into two main types: geostatistical modelling which integrates inventory data and geographical and environmental factors; and mechanical modelling which arrives at forest carbon stocks through simulations (Sun & Liu, 2020).

In the tree plantations, this study adopted a ground-based non-destructive method that involved measuring the DBH and the height of trees and converting the measurements into tree biomass using an allometric equation. On the other hand, a destructive approach was used in herbaceous vegetation. The ground-based method was used because of its relatively high accuracy, readily available allometric equations to apply and it is less destructive in forests (Chave et al., 2014; Houghton et al., 2012).

2.4 Land use/cover change predictions and carbon stocks for Mbarara city

2.4.1 Modelling land use/cover change

Land use/cover modelling has become an indispensable tool for understanding and predicting the intricacies of future urban expansion to inform sustainable urbanization (Gaur, 2023). Numerous models including, the analytical equation-based, statistical, evolutionary, cellular, Markov, hybrid, expert system, and multiagent models (Gaur, 2023; L. Liu et al., 2020; Ruben et al., 2020; Subedi et al., 2013) are used for LUCC analysis and predictions. These models analyse the drivers and outcomes of land use/cover changes.

The CA-Markov model is a frequently utilized modelling technique and tool for identifying and forecasting in land use and cover transformations (Liping et al., 2018; Satya, 2020; Wangyel et al., 2021). According to Liping et al. (2018), this model forecasts the dynamics and characteristics of changes in land use and land cover over time by integrating the Markov chain and cellular automata (CA). The model is widely used by planners and scientists (Zhao & Peng, 2012) to investigate land use/cover change patterns and processes, urban growth, modelling and watersheds because of its capacity to represent both spatial distribution and temporal changes in the landscape through time.

Recent studies on the prediction of future land use have made use of Markov chain analysis (Meli et al., 2019). It can determine the probability of trends from the earlier images to the later images to identify the transition tendency of the future LUCC probability according to the specific years' prediction. According to Meli et al. (2019), it can ascertain the likelihood of trends from the earliest to the latest images to pinpoint the future LUCC probability's transition tendency. A transfer matrix and a probability transfer matrix are produced during the Markov chain's primary processing to forecast future trends in land use/cover change.

Various studies have used the CA-Markov model to predict urban land use change with varying results. For instance, a simulation of the urban expansion of Nizwa city in Oman revealed that the built-up area would grow from 31.1% of the land area in 2018 to 34.2% in 2028 and 48.3% in 2038 while vegetation would reduce from 0.57% to 0.52% and 0.02% for the same periods; bare land and rocky land would equally reduce dramatically (Mansour et al., 2020). In Mumbai, India a study by Vinayak & Lee (2021) predicted that by 2050, the urban class would cover 46.87%

(1328.8 km²) of the study area, an increase of 14.31% for 922.93 km² (32.56%) in 2011. Equally, forest coverage was predicted to grow by 2.05% compared to agriculture and sparsely vegetated areas which would decline by 16.87%. Similar results were observed in Kathmandu city in Nepal, Warangal City in India and Thimphu in Bhutan (Satya, 2020; Wang et al., 2020; Wangyel et al., 2021) predicted increase in the grey spaces while vegetation and other land use types would decline.

In Africa, Koko et al. (2020) modelled the LULC of Zaria City in Nigeria for the years 2035 and 2050 using the CA-Markov model. The study revealed continuous expansion of the built-up areas and vegetation at the expense of barren land due to the reforestation, agricultural development and urbanization processes. Likewise, in Addis Ababa, Ethiopia, the model predicted a progressive increment of built-up spaces while consuming the ecologically valuable LULC types (Mohamed & Worku, 2020). The results revealed that in 24 years, the built-up areas grew by 277% while forest coverage dropped from 34% in 1991 to 6.5% in 2015. On the other hand, the projection for 2025 indicated that urban extent will significantly increase to 70% from 44% in 2015. In Uganda, Taubenböck et al. (2013) predicted the land use/cover for Kampala city revealing that by 2040 the built-up areas will cover 18.96 km² from 7.79 km² in 2010, reflecting a rapid increase.

2.4.2 Carbon Stock Predictions

Land use land cover changes affect carbon storage in terrestrial ecosystems (Houghton, 2012). The rapid expansion of built-up areas leading to the loss of vegetation such as forests and grasslands can lead to a substantial loss of stored carbon (Feng et al., 2020). The prediction of future carbon stocks is usually based on a prediction of land use change and relies on baseline data to project future stocks (Dumitraşcu et al., 2020). Areal expansion of a carbon sink such as forests or grasslands implies an increase in the amount of carbon sequestered while a decrease leads to emissions (IPCC, 2006). A study in the Hunan province of China (Zhu et al., 2023) used land use data between 2000 and 2020 to model land use change by 2040. The findings show that urban construction will lead to a decline in arable land and vegetation causing a carbon reduction.

2.5 Gaps in Literature

Several LULCC studies have been conducted globally both in rural and urban environments. Massive transformations have been reported, especially the transformation of forests to agricultural lands and settlements. In the urban areas, built-up land has been noted to expand dramatically, particularly in the low-income countries. In the area of study, one study on land use and land cover changes was carried out for the period 1990-2014, which is a long time. Moreover, for the previous study period, the Mbarara urban area covered a smaller area and was designated as a municipality. This study analyzed land use/cover dynamics between 2013 and 2023 to reveal recent data for Mbarara City. In addition, land use/cover analysis focus on general urban land use changes and urban sprawl. The focus of this study was land use/cover dynamics with specific emphasis on urban green spaces.

A multiplicity of studies has analyzed carbon stocks in terrestrial ecosystems and both the above- and belowground carbon pools have been considered. Remote sensing data is dominant for large-scale studies of biomass. Regional studies employ remote sensing and are supplemented by field measurements. Allometric equations have been applied in forest ecosystems to estimate biomass and carbon stock densities. However, most studies have concentrated on forests and agroecological systems. This study examined carbon stocks in an urban area focusing on urban green spaces - vital carbon sinks that contribute to local and regional climate change mitigation.

In addition, studies on land use/cover predictions have been conducted in some African cities and Kampala. However, no study has been done in the newly created regional cities in Uganda including Mbarara. Yet still, no study has been done linking land use/cover change and carbon stocks in urban green spaces.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter covers the methodology that was employed in the study. It covers the description of the study area, research design, data collection methods, and data analysis.

3.2 Description of the study area

3.2.1 Location

The study was conducted in Mbarara city, in South-Western Uganda, 266 Kilometers from Uganda's capital city, Kampala, along Kabale road (Figure 2). Longitudinally, it is located $30^{\circ}37'$ East of Greenwich and $0^{\circ}36'$ South of the Equator, at a mean altitude of 1,432 meters above sea level and occupies a land area of approximately 449.09 Km² (44,909 hectares) (Mbarara City Development Plan 2020/2021-2024/25; Sengendo et al., 2012). Administratively, Mbarara City is made up of two political divisions that is Mbarara City South (191.49 Km²) and Mbarara City North (257.6 Km²) which are divided into six administrative divisions, namely: Kakoba, Nyamitanga, Kakiika, Nyakayojo, Biharwe and Kamukuzi. (Mbarara City Development Plan 2020/2021-2024/25).

Mbarara City was selected for this study because it is undergoing rapid and haphazard growth which is destroying the ecosystem and has the potential to cause adverse effects of climate change characterized by urban heat islands, heatwaves, pollution, flash floods and environmental diseases. In addition, the elevation of Mbarara municipality to a city status in 2020 has increased the demand for infrastructure including housing facilities which in turn puts more pressure on the ecosystem exacerbating the already worrying environmental crisis (Bwanika, 2016; Mbarara City Development Plan, 2020/21-2024/25).

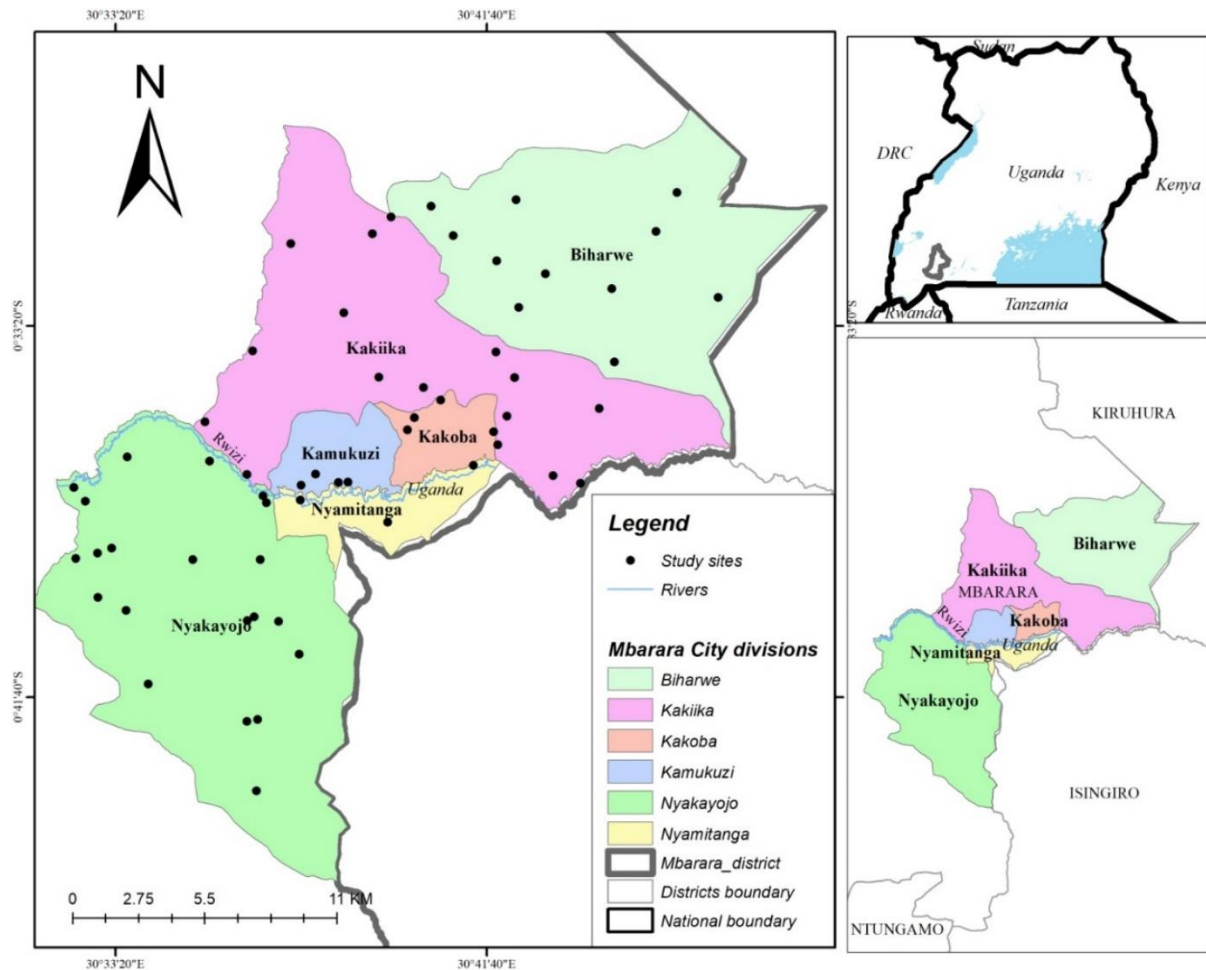


Figure 3. 1: Map of Mbarara city

3.2.2 Geology, soils and vegetation

Mbarara city is part of the Buganda-Toro rock system composed of relatively soft rocks that are easily weathered which has given rise to clay loams, sandy loams as well as murram in many parts. The hilltops are characterized by lateritic caps because of leaching. Savannah grassland characterized by short grass and scattered bushes is the dominant natural vegetation type (Westerhof et al., 2014; Sengendo et al., 2012). The nature of soils has largely favoured the growth of grassland vegetation (NEMA, 2019)

3.2.3 Relief and drainage

Mbarara City is in a hilly area interrupted by small and shallow valleys which is the raised part of the East African Rift Valley system. River Rwizi which navigates through the City is the major drainage feature (Sengendo et al., 2012). The river system provides an opportunity for conservation of wetlands which offer critical ecosystem services including carbon storage.

3.2.4 Climate

Mbarara City falls within the tropical savanna climatic zone, receiving an annual rainfall of 1,125 mm distributed in two rainfall seasons separated by two dry seasons. The mean annual temperature is 25⁰C. (Sengendo et al., 2012). The nature of climate can sustain a wide range of vegetation types including trees for environmental sustainability.

3.2.5 Population

The city (formerly Mbarara Municipality) had a population of 195,031 in 2014 and currently has an estimated night population of 250,000 and a day population of 300,000 (UBOS, 2016; Mbarara City Development Plan 2020/2021-2024/25). Accordingly, the 2024 projected population of Mbarara City North is 126,973 while Mbarara City South is 190,719 people. Rapid population growth triggers massive land use changes endangering the ecosystem soundness of the region (Bwanika, 2016).

3.2.6 Land use activities

The main land use activities are small-scale farmlands for crops and animals, built-up areas including housing, commercial buildings, manufacturing establishments and road networks, and planted forests. In the housing sector, there is notable dominance of low and medium-income houses and rapid growth of informal settlements (Bwanika, 2016; Mbarara City Development Plan 2020/21-2024/25, 2024; Sengendo et al., 2012). Urban land use, especially the rapid growth of informal settlements, and small-scale farming is a critical threat to the survival of urban green spaces which are the main carbon sinks in the city (Oviantari et al., 2018).

3.3 Research design

The study adopted both cross-sectional and longitudinal designs using quantitative data. The cross-sectional approach involved collecting quantitative field data on biomass for carbon stock computation. The longitudinal aspect related to the analysis of historical, current and prediction of future land use/cover changes reconstructed from geospatial data for 2013, 2018 and 2023.

3.4 Data collection methods

Quantitative data acquired from both primary and secondary data sources was used in this study. Primary data involved field measurements of aboveground biomass for trees, herbs and grass. Ground-truthing and recording of the GPS locations of different land use/cover types and sample sites were done. Secondary data sources included geospatial analysis of Landsat (30 x 30) images for the 2013, 2018, and 2023 series.

3.4.1 Quantification of land use/cover changes in Mbarara City between 2013 and 2023

This subsection highlights the sources of data and procedure for image classification, analysis and validation.

3.4.1.1 Data sets

Several multi-spectral satellite images were used to assess and quantify LULC changes. Landsat-8 OLI/TIRS (Operational Land Imager) (30 x 30 m) images for 2013 and 2018, and Landsat-9 for 2023, were downloaded from the U.S. Geological Survey's (USGS) Earth Explorer website (<https://earthexplorer.usgs.gov>). All images used were obtained for the dry months (June and July) with low cloud cover. The Landsat-8 and 9 were used in the study because of their high resolution which translates to high accuracy in capturing temporal and spatial variations in land use/cover of a given region, and they are free to access. Details of the used satellite images are presented in Table 3.1.

Table 3. 1: Specifications of the satellite imageries

Year	Image	Satellite	Cloud cover
2013	"LC08_L2SP_172060_20130706_20200912_02_T1"	"LANDSAT_8"	1.39
2018	"LC08_L2SP_172060_20180618_20200831_02_T1"	"LANDSAT_8"	4.85
2023	"LC09_L2SP_172060_20230710_20230712_02_T1"	"LANDSAT_9"	1.43

3.4.1.2 Preprocessing and processing of satellite images

Radiometric and geometric image corrections were done to define true geolocation positions of images and improve feature distinctions on the earth's surface (Sowmya, 2020). Preprocessing was done in ArcMap 10.8. The unrefined image bands 1-7 for Landsat 8 and 9 were imported into ArcMap and composited into a single Multispectral image using the band composite tool. The Mbarara City boundary shapefile was used to extract the region of interest by masking. Iso Cluster Unsupervised classification and Maximum likelihood supervised classification were applied to obtain LULC classification (Rwanga & Ndambuki, 2017; Sowmya, 2020). A training sample was generated for each year using the composite images and was validated by the Iso-Cluster map and the World Imagery base map. Six classes were produced based on the Uganda National Biomass Study technical report of 2005 guidelines (NFA, 2009), as illustrated in Table 3.2.

Table 3. 2: Description of land use/cover types in Mbarara City

Land use/cover type	Description
Built-up areas	Artificial surfaces- buildings and roads, both tarmac and marram/soil
Bushland	Vegetation dominated by bush, scrub and thicket growing together as an entity, but not exceeding an average height of 4m
Cropland	Small-scale farmland with shrub and herbaceous crops mainly banana plantations, pineapples, coffee, sweet potatoes etc.
Grassland	These are rangelands, grazing grounds, improved pastures or natural savannah grassland. Various trees - bush/woody vegetation frequently occur on this land, but grass dominates the landscape.
Tree plantations	Planted trees/woodlots (Composed of mainly eucalyptus and pine)
Wetland	Waterlogged areas (seasonal and permanent)/comprise permanent wetlands; usually with papyrus and reeds.

3.4.1.3 Image accuracy assessment

Accuracy assessment aims to validate the information value of processed data to the user (Rwanga & Ndambuki, 2017). Image accuracy for the land use/cover maps of 2013, 2018 and 2023 was assessed. In total, 100 random points were generated within the study area boundary for all the years. The random points were exported as klm files to Google Earth where they were used to validate the classified land uses/ covers on the ground. Validated points were used to compute the confusion matrix to determine the User's and Producer's accuracy and the Kappa values (Rwanga & Ndambuki, 2017).

$$\text{Overall accuracy} = \frac{1}{N \sum x_{ii}} = 1$$

Where:

x is the individual cell values, x_{ii} is the total number of observations in row i and column i N is the total number of classes and N=total number of samples.

Kappa coefficient

$$Kc = \frac{N \sum x_{ii} - \sum (X_{it} \times t_i N)}{N^2} = 1 - \frac{\sum (x_{it} \times X_{it})}{N^2}$$

Where K_c is the kappa coefficient, N is the total number of samples, x_{ii} is the sum of the correctly classified pixel, r is the number of rows in the matrix, x_{it} and x_{ti}, are the marginal totals of row i and column i respectively. According to Rwanga & Ndambuki (2017), Kappa Coefficient values of 0.81 are considered to be in excellent agreement, 0.61- 0.80 are in good agreement and below 0.20 to 0.61 are considered poor.

3.4.1.4 Determination of the transitions and trends of land use/cover changes in Mbarara city

The analysis of LULC changes conducts a spatial overlay with the land-use status quo spatial information at the two time points under the ArcGIS geographic information software (Hong et al., 2011). LULC changes were analyzed based on the degree (magnitude) of change (C),

percentage of change (P%), and rate of change (R) in each class using equations 1 and 2 (Aldileemi et al., 2023).

$$C_i = L_i - B_i \quad \text{Equation (1)}$$

$$P_i = \frac{C_i}{B_i} \times 100 \quad \text{Equation (2)}$$

Where i represents land use class, B_i and L_i are the areas in Ha with the earliest and latest LULC respectively. T is the period between B_i and L_i .

Change detection was also performed using the transition matrix. The classified raster maps for 2013, 2018 and 2023 were converted to polygon vector layers for spatial analysis of the GIS environment. To establish total area changes between different LULC classes from 2013 to 2018, 2018 to 2023 and 2013 to 2023, cross-tabulation (intersection) was performed in ArcMap 10.8. A transition matrix for the periods studied was generated and statistics were exported to Excel to generate the Land use/cover transition statistics and transition graphs. Finally, the land use/cover types for successive years were regressively analyzed in response to time. This was done to determine whether the changes in trend were significant or insignificant over time.

3.4.2 Estimation of the aboveground carbon stocks in the green spaces

This subsection covers the sampling plan and data collection methods for biomass and carbon stock determination.

3.4.2.1 Sampling procedure

To compute the carbon stocks, Satellite imagery was used to classify the different vegetation types and identification of their location. The resultant strata included tree plantations, wetlands, bushland and grasslands. A nested two-stage sampling was used to determine the sampling plots for the different vegetation classes. Grids (10 x 10 cm) were laid over the study area map and boundaries of the distinct vegetation classes within the study area delineated. The meeting points between the vegetation class boundaries and the grid intersection points were taken as sampling

locations giving a total of 60 samples across the different green spaces. The sample locations were identified in the field using a GPS. A non-destructive sampling approach was employed for the trees and destructive methods for shrubs and grasses. The sampled plots were diverse covering all the vegetation types and spatial distribution as outlined in the UNFCCC guidelines (UNFCCC, 2015).

3.4.2.2 Estimation of plot-level biomass

Data from the different vegetation types was obtained using destructive and non-destructive methods. For tree assessments, the height and diameter at breast height (DBH) of all trees with a diameter ≥ 5 cm in the sample points were measured and the biomass was computed using the allometric equation applicable to dry tropical forests (rainfall below 1500 mm year⁻¹) (Chave et al., 2014)

$$AGB_{est} (kg) = 0.0673 X(pD^2H)^{0.976} \quad \text{Equation (3)}$$

Where:

p = wood specific gravity (oven-dry wood/green volume (g/cm³)). The mean p for tropical forests in Africa is estimated at 0.5 g/cm³ (Mugagga, 2015)

D = tree diameter at girth height (1.3m)

H = height of the tree.

The individual AGB for all trees in the plot was summed up to obtain the total AGB for the entire plot. Total Carbon stock was determined by multiplying biomass by 0.47 (Chaplin-Kramer et al., 2015; IPCC, 2006).

$$\text{Total Carbon stock (kg)} = 0.47 * \text{Biomass} \quad \text{Equation (4)}$$

The biomass of the shrubs, herbs and grasses, were estimated using destructive methods. A nested design was employed to determine sample plots measuring 40 x 40 meters. Within the designated sample plots, five nested quadrants measuring 1 x 1 meter were laid at the vertices and the centre.

All the shrubs, herbs and grasses that fell in the designated quadrants were harvested and fresh weight was established in the field. The harvested vegetation from all five quadrants within each sample plot was thoroughly mixed and subsamples were picked to represent the plot, packed in prelabelled bags and taken to the laboratory, and oven-dried at 65°C to determine their dry mass (Amoatey & Sulaiman, 2020). Biomass carbon was analysed in the laboratory as percentage carbon and total carbon calculated following the Walker et al. (2012) equation. Biomass carbon stock from shrubs, herbs, wetlands and grasses was estimated as:

$$\text{Above ground carbon (kg)} = \text{Dry mass} \times \% \text{ carbon} \quad \text{Equation (5)}$$

The total biomass from all the sample locations in the different strata was summed up to compute the carbon content for each vegetation type. Finally, the carbon stocks of individual plots were calculated to determine the carbon stocks per hectare.

3.4.3 Land use/cover change prediction

LULC scenarios in Mbarara City were predicted using the CA-Markov model in this study based on previously identified imagery from 2013 and 2023. Land Cover Modeler (LCM) modelled potential LULC scenarios using historical LULC maps and several driving forces. As stressed by Wang et al. (2016), choosing the input driving variables was also crucial for predicting future LULC maps in Mbarara City. The driving variables considered in LCM in this study are elevation, slope, distance to a river, and distance to the road. The dependent and independent factors were used to predict LULC change. In this study, the driving variables are considered dependent, and LULC maps are considered independent variables. It is important to note that the choice of variables and indicators may, to some extent, result in certain variations in the simulation results or parameters of the model, which will affect the forecast of LULC change (Shiferaw, 2022). In terms of distance from the road, for instance, if the region is extremely close to the road, the rate of urbanization is quite high, and vice versa. This also holds for other determining variables.

Therefore, the modelling approach; CA-Markov integrated into TerrSet Land cover modeler was used to simulate future LULC scenarios. Before forecasting the changes in the land covers, a transition probability in the Markov model was done to assess the possibility of LULC changing

from one class to another based on area suitability transitions and the existence of driving forces. The Transition modelling keeps track of the likelihood that each land use class will shift into a different class.

In this study, four steps were taken to predict future land cover/use changes in Mbarara City in scenarios of 2043 using the Land Cover Modeler (LCM). These steps include (a) change analysis of past LULC maps (2018, 2023); (b) creating transition probability matrixes; (c) validating the model by comparing actual and forecasted maps of the year 2023; and (d) prediction of future LULC maps for the years 2043, while accounting for driving forces during the process. Therefore, the Markov model analysis describes the probability of land cover change from one period (t) to another (t+1). The changes were calculated using a probability equation proposed by Bayes to predict land cover changes (Sang et al., 2011).

$$St + 1 = (Pij * St) \quad \text{Equation (6)}$$

Where, St is the state of the cell in the CA at time (t), $St + 1$ is the state of the cell in the CA at time (t+1) and Pij is the transition probability matrix.

In addition to maximizing the effectiveness of the used model, different iteration numbers—that is, the optimal number of iterations were used to forecast the land cover change map. These included modelling the land cover for the year 2043 using a 5*5 contiguity filter applied with 5 iterations; the model was then validated. The overall methodology adopted in this study is illustrated in Figure 3.2.

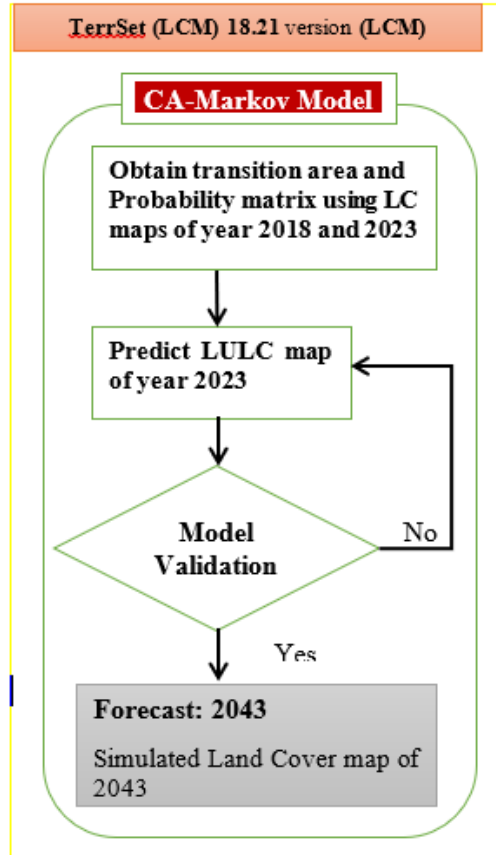


Figure 3. 2: The CA-Markov prediction model

3.4 Data analysis

Satellite images were processed in the ArcGIS platform to analyze land use/cover changes in Mbarara city for 2013, 2018, and 2023. Iso Cluster (unsupervised) and Maximum likelihood (supervised) classification methods were used. Land use classes were determined following the Uganda National Biomass study of 2005 (NFA, 2009). Quantitative land use/cover data was analyzed using the land cover conversion matrix in the ArcGIS 10.8 version to determine land use/cover transitions. Land use/cover transitions data were exported to Microsoft Excel for visualization and presentation.

Biomass and carbon stock data were entered into Microsoft Excel to analyze descriptive (mean and standard deviation). A one-way analysis of variance (ANOVA) was performed to test the differences in mean aboveground biomass and carbon stocks among the different green spaces.

3.5 Ethical considerations

The researcher obtained a field introductory letter from the Directorate of Research and Graduate Training through the Geography department to facilitate data collection (Appendix I).

Permission to access study sites was first sought from the city council's Natural Resources Office. Before accessing the sampling sites, informed consent was sought from the owners of private property and caretakers for public sites like NFA conservation areas (Appendix II).

Further still, the researcher ensured openness and transparency in communication with the stakeholders by clearly explaining the purpose of the study to the community members whose properties were accessed for sample collection and tree biomass measurement.

CHAPTER FOUR

PRESENTATION AND DISCUSSION OF RESULTS

1.4 Introduction

This chapter presents the study's findings following the main objective of the study which was to establish how LULC changes affect carbon stocks in urban green spaces in Mbarara City. The findings are presented in line with the specific objectives namely, determining the land use/cover changes in Mbarara city between 2013 and 2023, quantifying current and historical carbon stocks in the urban green spaces, and predicting the land use/cover changes and carbon stocks for the year 2043.

4.2 Land use/cover changes in Mbarara City between 2013 and 2023

4.2.1 The spatial extent of land use/cover changes

The study analysed the spatial extent of land use/cover and the findings are presented in Figure 4.1.

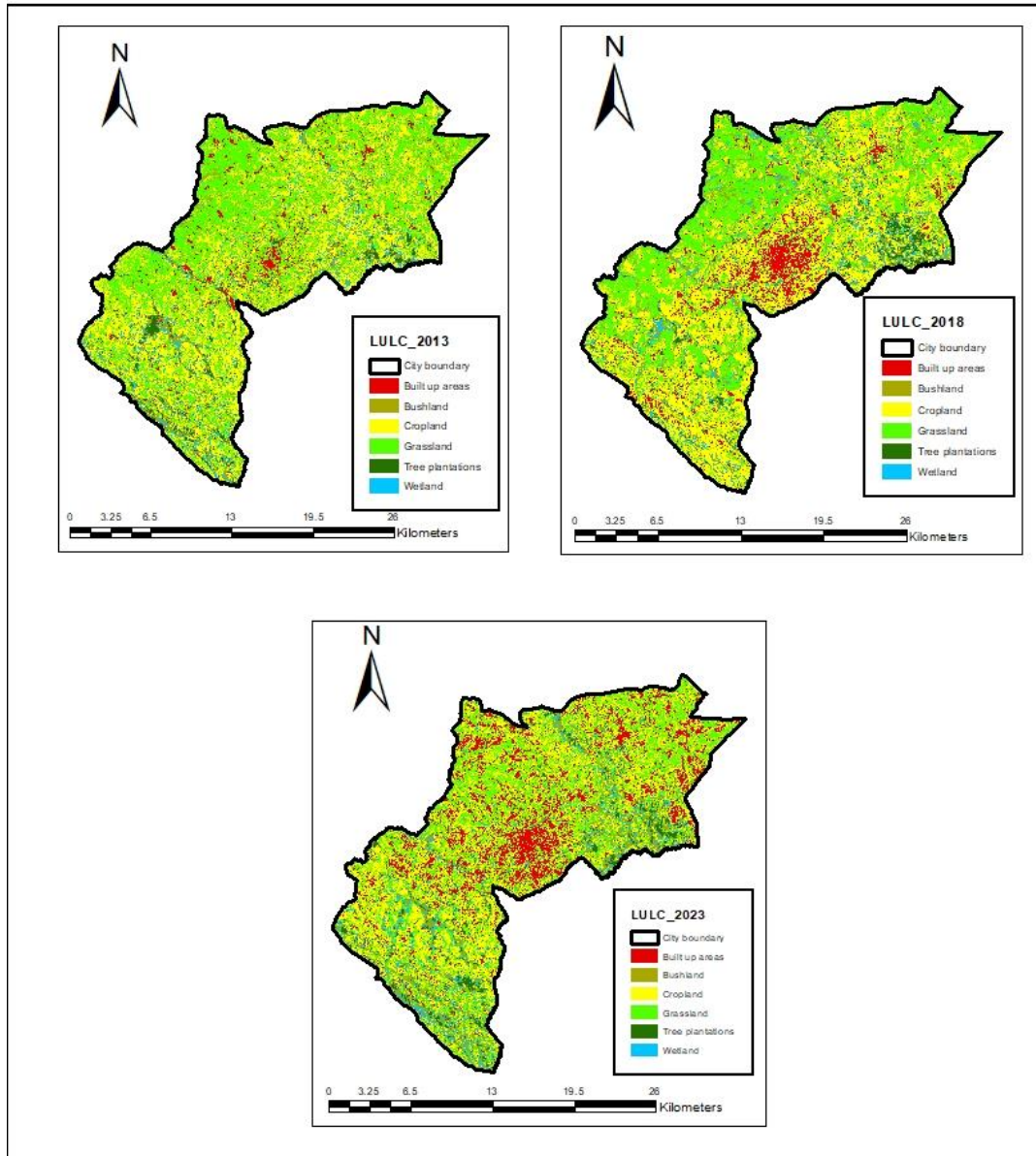


Figure 4. 1: Land use/cover changes for Mbarara City between 2013 and 2023

The findings in Figure 4.1 show that between 2013 and 2023, the built-up area expanded continuously. Grassland and cropland were the largest land use/cover types in all the years. Specifically, the results show that in the year 2013, grassland and cropland were the dominant land use/cover types while the built-up areas were concentrated in the central part of the city within Kakoba and Kamukuzi divisions and the northeast around the Biharwe trading centre. Tree plantations and bushland vegetation can be observed in many areas particularly along river Rwizi

in the central, to the southeast in Kakiika division, and the western and southwestern part in Nyakayojo division.

In 2018, there was a noticeable expansion of the built-up areas outwards from the central part of the city, around the Biharwe trading centre in the northeast, and in the Nyakayojo division in the west at the expense of grassland and cropland. There is a recognisable loss of land under tree plantations, bushland and wetland vegetation which have been converted to built-up and cropland in Nyakayojo division in the western and southwestern parts and Biharwe division in the northeastern. However, tree plantations expanded in the Kakiika division in the southeast. In 2023, built-up areas increased tremendously in the central, north, north and western parts of the city taking up much of what was formally land covered by vegetation, particularly grasslands, bushland wetland and cropland. There is an expansion of planted trees in the hilly parts of Nyarubungo, Kichamba and Bugashe in Nyakayojo division in the south and Nyakinengo and Nyabuhama in Kakiika and Biharwe divisions in the East and Northeast of the city.

The accuracy of the subsequent LULC maps for the 2013, 2018 and 2023 study years presented in Figure 4.1 was assessed and the results are presented in Table 4.1 below.

Table 4. 1: Accuracy assessment results

Year	2013	2018	2023
Total accuracy (%)	89.9	91	86.0
Kappa coefficient	0.88	0.86	0.78

The results in Table 4.1 show that the LULC maps for 2013, 2018 and 2023 had an overall accuracy of 88.9%, 91% and 86% and Kappa statistics of 0.88, 0.86 and 0.78 respectively for land use/cover classification. Therefore, the overall results are substantial for further analysis and change detection.

Furthermore, the study analysed LULC change between 2013 and 2023 and the results are presented in Table 4.2.

Table 4. 2: Land use/cover changes for Mbarara City (2013-2023)

Land use/cover types	2013		2018		2023		Change 2018		Change 2013-2023	
	Area (Ha)	%	Area (Ha)	%	Area (Ha)	%	Area (Ha)	%	Area (Ha)	%
Built up areas	1682	3.8	3485	7.9	6880	15.6	1803	4.1	3395	7.7
Bushland	4836	11.0	4074	9.2	4458	10.1	-762	-1.7	384	0.9
Cropland	16656	37.8	17245	39.1	14822	33.6	589	1.3	-2423	-5.5
Grassland	16920	38.4	15472	35.1	13899	31.5	-1448	-3.3	-1573	-3.6
Tree plantations	1245	2.8	1272	2.9	1380	3.1	27	0.1	108	0.2
Wetland	2730	6.2	2522	5.7	2630	6.0	-208	-0.5	108	0.2
Total	44070	100.0	44070	100.0	44070	100.0				

The findings Table 4.2 shows that in the year 2013, grassland, cropland and bushland were the dominant LULC types covering 16,920 Ha (38.4%), 16,656 Ha (37.8%) and 4,836 Ha (11%) respectively. However, grassland consistently contracted during the study period to 15,472 Ha (35.1%) in 2018 and 13,899 Ha (31.5%) in 2023. At the same time, cropland slightly expanded to 17,245 Ha (39.1%) in 2018 before reducing to 14,822 Ha (33.6%) in 2023. Bushland reduced to 4074 Ha (9.2%) in 2018 and slightly expanded to 4458 Ha (10.1%) in 2023.

On the other hand, tree plantations, wetlands and built-up areas covered the smallest land area in 2013. However, built-up areas and tree plantations experienced continuous expansion throughout the study period. Built-up expanded from 1,662 Ha (3.8%) in the year 2013 to 3,485 Ha (7.9%) in 2018 and 6,880 Ha (15.6%) in 2023 while tree plantations expanded from 1,245 Ha (2.8%) to 1,272 Ha (2.8%) and 1,380 Ha (3.1%) in the year 2013, 2018 and 2023 respectively. Meanwhile, wetlands decreased from 2,730 Ha (6.2%) to 2,522 Ha (5.7%) between the years 2013-2018 and finally increased to 2,630 Ha (6.0%) in the year 2023. The LULC changes for the study area are further illustrated in Figure 4.2.

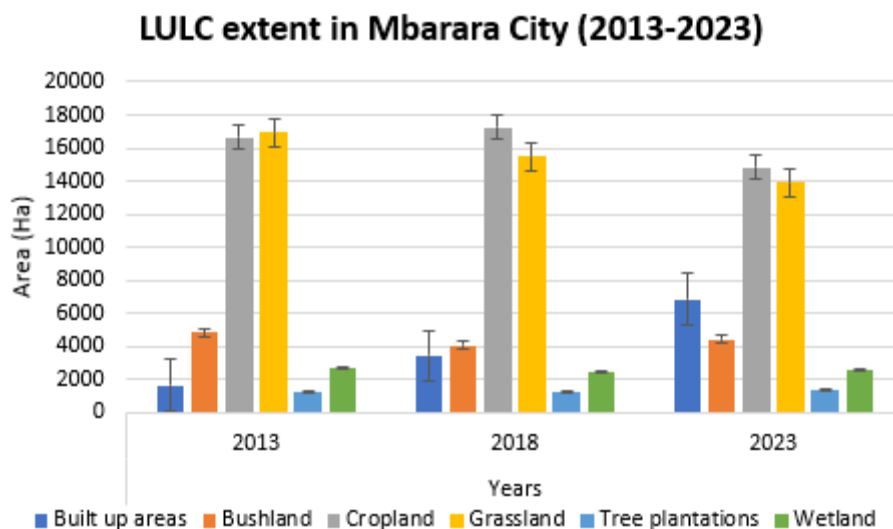


Figure 4. 2: LULC changes in Mbarara City (2013-2023)

4.2.2 Transitions in land use/cover changes in Mbarara city.

Analysis of the transitions across various LULC classes for the 2013 to 2018 study period was carried. The results are presented in Table 4.3. It highlights the losses and gains in the area and

Table 4. 3: Land use/cover transitions (Ha) in Mbarara City (2013-2018). The figures in brackets represent percentages

<i>LULC changes (Ha)</i>	2018					
	Built up areas	Bushland	Cropland	Grassland	Tree plantations	Wetland
2013 Built up areas	958 (56.8)	32 (1.9)	279 (16.6)	401 (23.8)	3 (0.2)	12 (0.7)
2013 Bushland	229 (4.7)	806 (16.7)	1,545 (32)	1,360 (28.1)	310(6.4)	585 (12.1)
2013 Cropland	355(21)	1,615 (9.7)	8,533 (51.2)	4,876 (29.3)	287 (1.7)	988 (5.9)
2013 Grassland	1,930 (11.4)	696 (4.1)	5,539 (32.7)	8442 (49.9)	78 (0.5)	232 (1.4)
2013 Tree plantations	4 (0.3)	384 (30.9)	160 (12.9)	58 (4.6)	441 (35.4)	198 (15.9)
2013 Wetland	18 (0.7)	537 (19.6)	1,182 (43.2)	332 (12.1)	151 (5.5)	515 (18.8)

Note: The bold diagonal values indicate the stable areas.

The results in Table 4.3 revealed that transitions occurred across all LULC classes. Built-up, cropland and tree plantations registered net gains while bushland, grassland and wetland classes registered net losses in land area. Specifically, the results show that by the year 2018, 56.8% of the original built-up area in the year 2013 was still intact while 23.8% had been converted to grassland, 16% to cropland and less than 3% transferred to wetland, bushland and tree plantations. At the

same time, a substantial area of grassland (11.4%), bushland (4.7%) and cropland (2.1%) had been converted to built-up by the year 2018. The bushland cover was highly unstable with only 16.7% of the area remaining unchanged while the largest area (83.3%) had been transferred out to other land use/cover types. Specifically, 32% of the bushland cover had been converted to cropland, 28.1% to grassland and 12.1% to wetland. Conversely, 30.9% of tree plantations, 19.6% of wetland and 9.7% of cropland had converted to bushland. In the cropland land use, 51.2% remained stable in 2018 while 29.3 % had been converted to grassland, 9.7% to bushland, and another 9.7% to wetland, built-up and tree plantations. On the other hand, cropland gained 43.2% of wetland, 32.7% of grassland, 32% of bushland, 16.6% of built-up and 12.9% of tree plantations by 2018.

By 2018, the grassland area had lost 32.7% which was converted to cropland, 11.4% to built-up and only 6% to bushland, tree plantation and wetland while 49.9% remained stable. Equally, grassland gained predominantly from 29.3% of cropland, 28.1% of bushland, 23% of built-up and 12.1% of wetland. Tree plantations area was unstable with only 35.4% remaining unchanged while 30.9% had been converted to bushland, 15.9% to wetland and 12.9% to cropland by 2018. At the same time, tree plantations gained 6.4% of bushland and 5.5% of wetland. By 2018, the wetland area retained only 18.8% of the original land area in 2013 while 43.2 % had been converted to cropland, 19.6% to bushland, and 12.1% to grassland. On the other hand, 15.9% of tree plantations, and 12.1% of bushland had been converted to wetlands.

The land use/cover transitions from 2018 to 2023 were also analysed and the results are presented in Table 4.4.

Table 4.4: LULC transition matrix for Mbarara City (2018-2023) The figures in brackets represent percentages

LULC changes (Ha)	2023						
	Built up areas	Bushland	Cropland	Grassland	Tree plantations	Wetland	
2018	Built up areas	2131 (60.1)	4 (0.1)	442 (12.6)	908 (26.0)	2 (0.1)	8 (0.2)
	Bushland	45 (1.1)	638 (15.7)	1,076 (26.4)	1,398 (34.3)	380.2 (9.3)	535 (13.1)
	Cropland	1,065 (6.2)	561 (3.3)	6584 (38.2)	7724 (44.8)	207.7 (1.2)	1101.2 (6.4)
	Grassland	1344.4 (8.7)	135.5 (0.9)	5,855.8 (37.9)	7771.3 (50.2)	48.0 (0.3)	314.5 (2.0)
	Tree plantations	6.1 (0.5)	312.2 (24.6)	92.9 (7.3)	139.4 (11.0)	593.7 (46.7)	127.0 (10.0)
	Wetland	20.2 (0.8)	474.9 (18.8)	569.9 (22.6)	763.7 (30.3)	147.8 (5.9)	544.1 (21.6)

Note: The bold diagonal figures represent the unchanged areas.

The results in Table 4.4 show that from 2018 to 2023 the greatest conversions happened between grassland, cropland and built-up classes. Built-up recorded the highest net gain of 1116.5 Ha compared to 124.3 Ha, 108.6 Ha and 108.4 Ha for bushland, wetland and tree plantations respectively. Additionally, the findings show that 61% of the original built-up area in the year 2018 remained intact by the year 2023 while 26% had been converted to grassland, 12.6% to cropland and only 0.4% to wetland, bushland and tree plantations. Conversely, the built-up area gained 8.7% of grassland and 6.2% of cropland. The bushland area remained highly unstable with only 15.7% (638.4 Ha) remaining intact from 2018 to 2023 while 84.3% transferred to other land use/ cover types. 34.3% of the original bushland area had been converted to grassland, 26.4% to cropland, 13.1% to wetland and the remaining 10.4% shared by tree plantations and built-up area. Despite the losses, bushland gained 24.6% of tree plantations, 18.8% of wetland 3.3% of cropland and 1% of wetland and built-up areas.

Additionally, cropland was unstable with only 38.2% of the area in 2018 remaining intact in 2023 whereas 44.8% was converted to grassland, 6.4% to wetland, and 6.2% to built-up area. Conversions to bushland and tree plantations were 3.3% and 1.2% respectively. On the other hand, cropland made gains of 37.9% of grassland, 26.4% of bushland, 22.6% of wetland, 12.7% of built-up, and 7.3% of tree plantations. Although averagely stable from 2018 to 2023 with 50.2% remaining intact, a significant land area of grassland was converted to cropland (37.9%) and built-

up area (8.7%). In contrast, grassland cover gained area majorly from cropland (44.8%) and bushland (34.3%). Further, the findings show that by the year 2023, only 46.7% of the original area under tree plantations in the year 2018 had stayed intact while 24.6%, 11%, 10%, 7.3% and 0.5% had been converted to bushland, grassland, wetland, cropland and built-up areas respectively. Finally, the wetland cover was equally unstable with 21.6% of the original cover remaining intact whereas the remaining was transferred out mostly to grassland (30.3%), cropland (22.6%) and bushland (18.8%). Inversely, wetlands gained 13.1% of bushland, 10% of tree plantations, 6.4% of cropland, 2% of grassland and 0.2% of the built-up areas.

They further analysed the overall land use/cover transitions for the period 2013 to 2023 and the results are depicted in Figure 4.3.

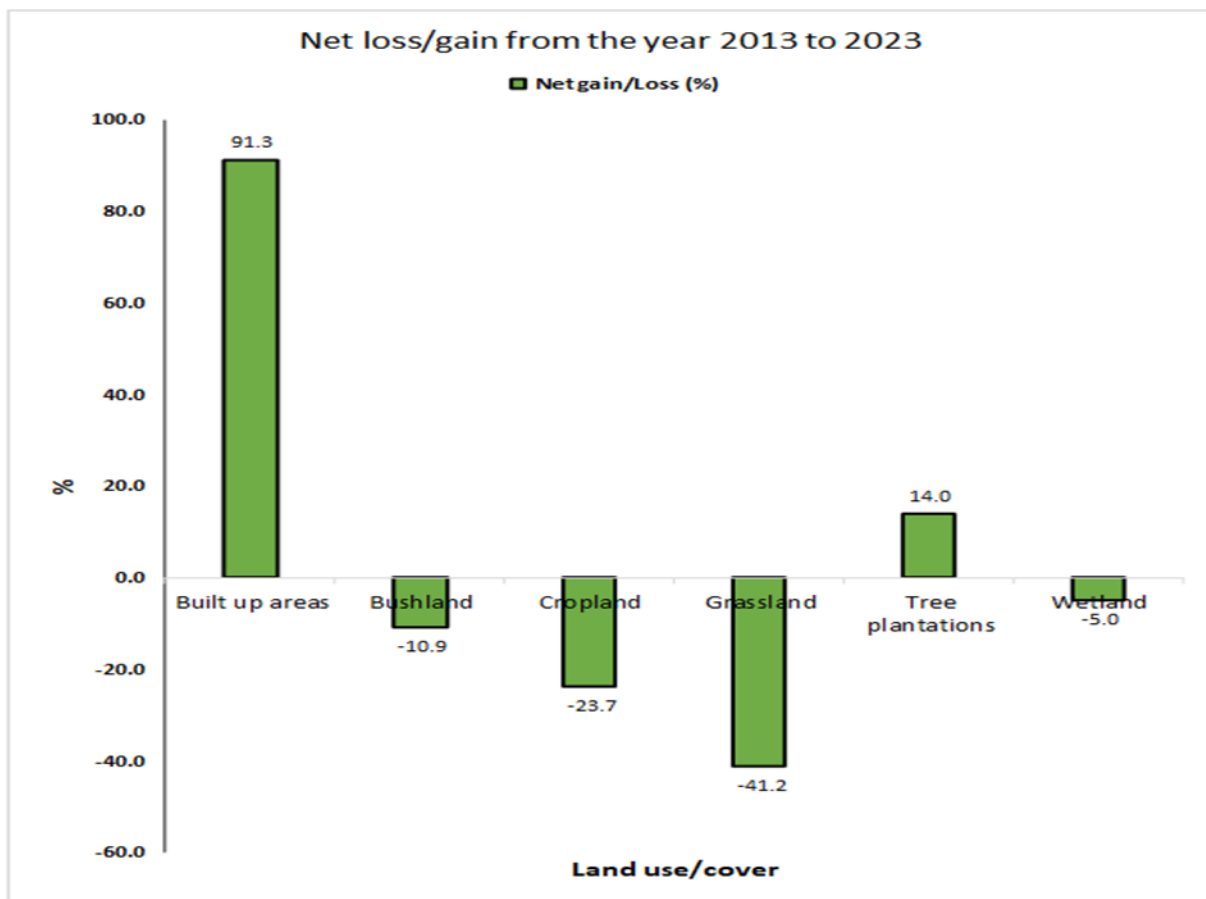


Figure 4. 3: LULC net gains/losses for Mbarara City (2013-2023)

The findings in Figure 4.3 show that all LULC classes underwent major transitions with built-up areas and tree plantations experiencing net gains while bushland, cropland, grassland and wetland experienced net losses. Specifically, the built-up area experienced the largest net gain of 91.3% while grassland experienced the highest net loss of -41.2%.

4.2.3 Trend analysis

The general trend of land use/cover changes for the period 2013 to 2023 was analysed to determine the significance of change and the results are shown in Figure 4.4

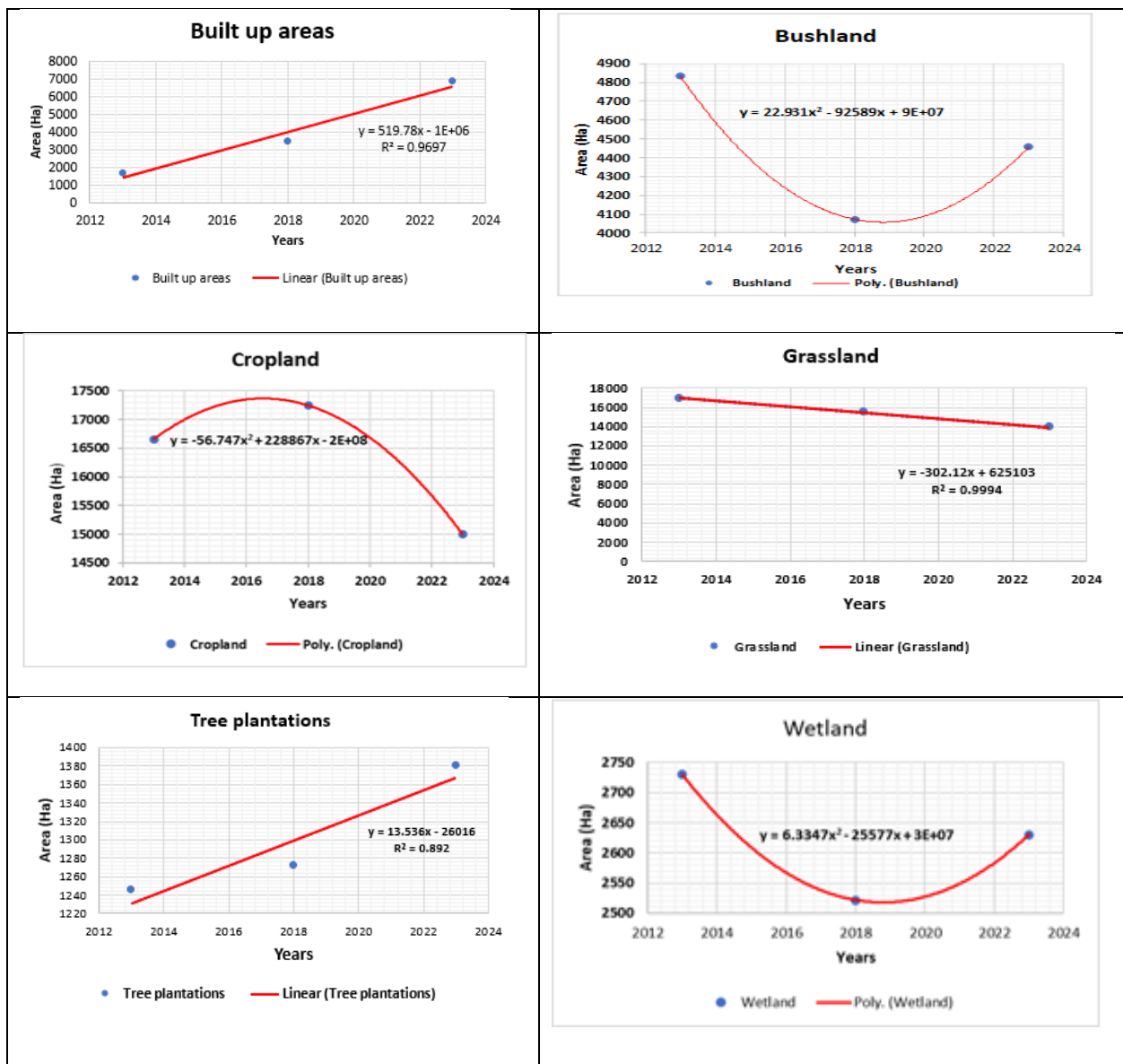


Figure 4. 4: Trend in Land use/cover changes in Mbarara city from 2013 to 2023

The results in Figure 4.4 show that the built-up area increased progressively throughout the study period ($y=519.78x-1E+06$, $R^2= 0.9697$) and bushland follows a quadratic trend ($y=22.931x^2-92589x+9E+07$, $R^2=0.2449$) with a downward oriented concavity. Equally, cropland followed a quadratic trend ($y= -56.747x^2+228867x-2E+08$) with a concavity oriented upwards and wetland decreased following a quadratic equation ($y= 6.3347x^2-2557x+3E+07$) with a downward oriented concavity. On the other hand, grassland significantly declined over time ($y= -302.12x+625103$, $R^2= 0.9994$) while tree plantations tended to increase linearly ($y= 13.53x-26016$, $R^2 = 0.892$).

4.3 The above-ground carbon stocks in the green spaces of Mbarara City

This section presents the findings on the carbon stock density and its spatial and temporal distribution within urban green spaces.

4.3.1 Total carbon stocks and carbon stock per unit area

The results for the aboveground carbon stock density were computed and presented in Figure 4.5 below. The results in Figure 4.5 show that the carbon stock per unit area varied across the different green spaces. Specifically, tree plantations had the highest carbon stock density of 40.3 t/ha, followed by grassland with 1.04 t/ha, bushland, with 0.8 t/ha and wetland with 0.66 t/ha. Cropland was not included in the carbon stock analysis because in this study it was not considered a permanent store of carbon because of the seasonality of the crops.

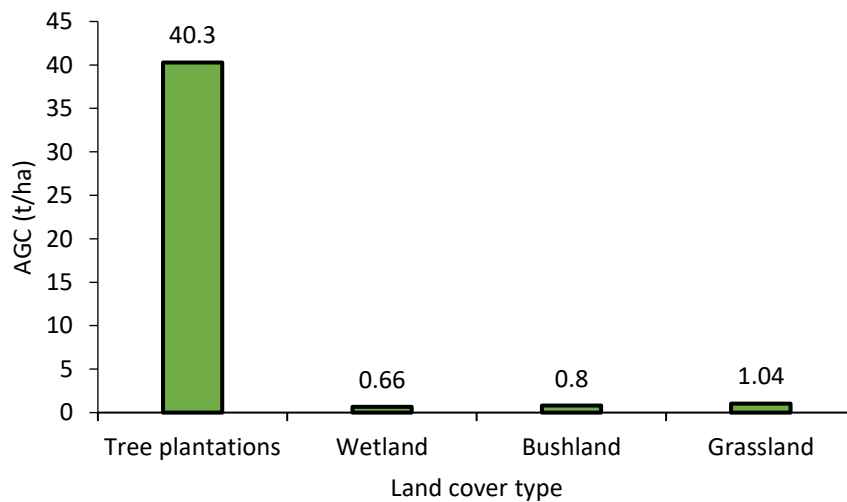


Figure 4.5: Carbon stock density in the different green spaces (2023)

To establish whether there were significant differences in the mean aboveground carbon stocks, an ANOVA was run and the results are depicted in Table 4.5. The results indicated a significant difference ($p < 0.0001$) in the mean aboveground carbon stocks across the different urban green spaces for 2023.

Table 4. 5: Analysis of Variance for total carbon stocks across the different land cover types for the year 2023

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	3	1726682.366	575560.789	2724.270	<0.0001
Error	116074	24523137.574	211.272		
Corrected Total	116077	26249819.940			

4.3.2 Carbon stock changes between the years 2013 and 2023

The study endeavoured to quantify the current and historical aboveground carbon stocks in the different urban green spaces and establish the spatial changes over the study period. The results are presented in Table 4.6.

Table 4. 6: Current and historical carbon stocks

LULC types	Carbon stocks (Gg)			Carbon stock changes (Gg)		% annual rate of change	
	2013	2018	2023	2018-2013	2023-2018	2018-2013	2023-2018
Bushland	3.90	3.26	3.57	-0.64 (-16.4%)	0.31 (9.5%)	-3.58	1.82
Grassland	17.60	16.09	14.52	-1.51 (-8.6%)	-1.57 (-9.8%)	-1.79	-2.05
Wetlands	1.80	1.66	1.74	-0.14 (-7.8%)	0.08 (4.8%)	-1.62	0.94
Tree plantations	50.20	51.26	55.63	1.06 (2.1%)	4.37 (8.5%)	0.42	1.63
Total	73.40	72.27	75.44	-1.13 (-1.5%)	3.17 (4.4%)		

The results in Table 4.6 show that an estimated 75.44 Gg of carbon was stored in various green spaces in 2023, the bulk of which was stored in the tree plantations (55.63 Gg) and grassland (14.52 Gg). The bushland and wetland stored an estimated 3.57 Gg and 1.74 Gg of carbon respectively. In addition, the findings show that the aboveground carbon stocks have been changing over the study period across the land use/cover types in the city. In the year 2013, the estimated total AGC was 73.40 Gg which decreased to 72.44 Gg in the year 2018 and finally increased to 75.44 Gg in the year 2023. Specifically, the tree plantations showed a consistent

increase in carbon stocks by 2.1% and 8.5% growing at an annual growth rate of 0.42% and 1.63% for the study periods 2013-2018 and 2018-2023 respectively. On the other hand, the aboveground carbon stocks in grassland decreased consistently by 8.6% (2013-2018) and 9.8% (2018-2023) at an annual rate of 1.79% and 2.05% for the respective periods. Carbon stocks in wetland cover decreased by 1.62% between 2013 and 2018 and increased slightly by 0.94% for the period of study between 2018 and 2023 while in the bushland cover it decreased by 3.58% and later increased slightly by 1.82% for the same periods.

4.3.3 Spatial distribution of above-ground carbon according to the land use/cover change over the study period

Figure 4.6 presents findings on the effect of land use/cover changes on the spatial distribution of carbon stock across the different land cover types in Mbarara City.

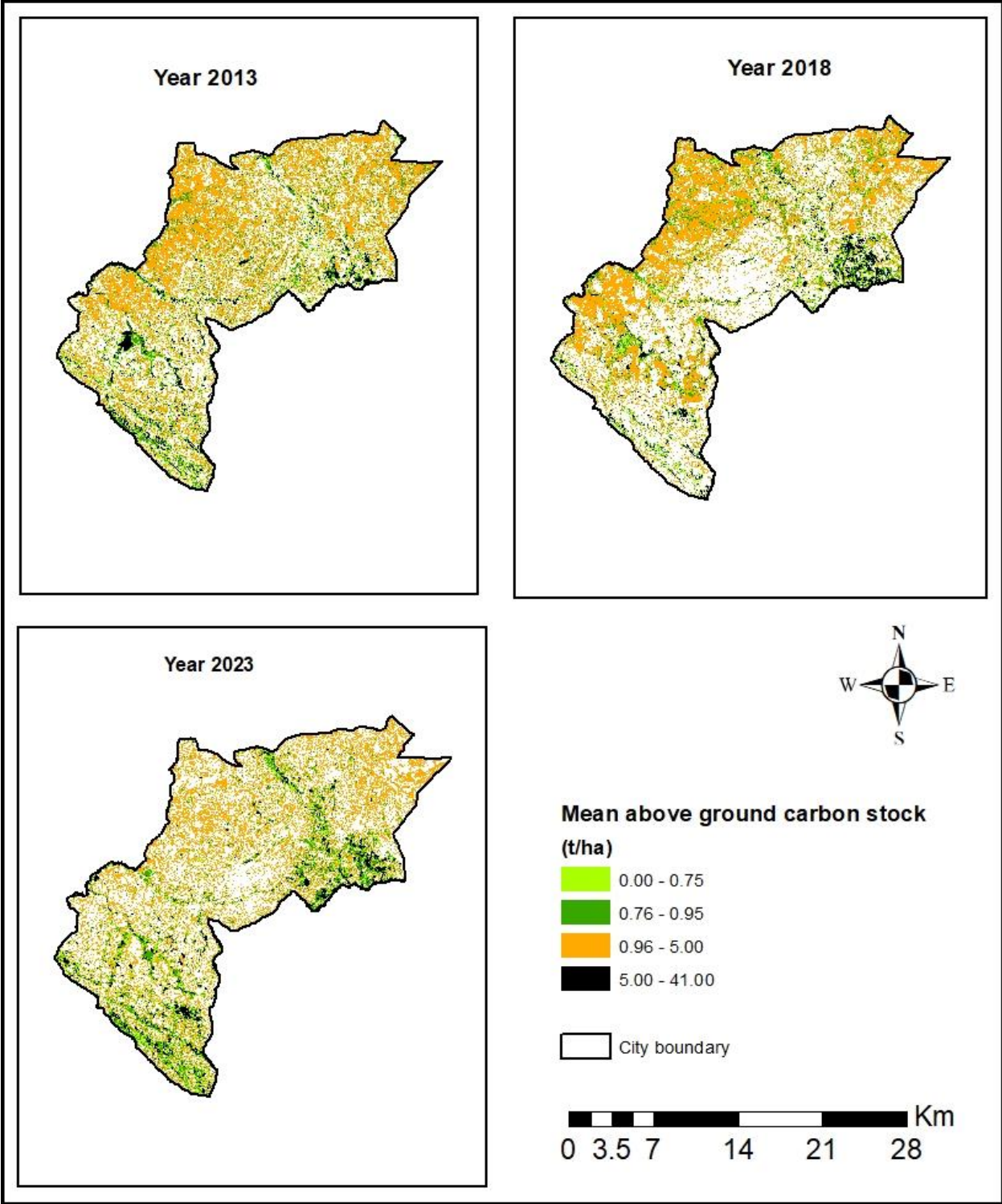


Figure 4. 6: Spatial distribution of above-ground carbon according to the land use/cover change over the study period

The results in Figure 4.6 show discernable shifts in the spatial distribution of mean above-ground carbon concentration for the study period. Specifically, in 2013, thick vegetation areas mainly tree plantations with high concentrations of aboveground carbon (5.00-41.00 t/ha) were distributed in the Southwest around the Rucece wetland system, along R. Rwizi and Nyarubungo hills in the south of Nyakayojo Division; in the city centre around Nyamityobora forest in Kakoba Division; and Rwemigina forest in Kakiika Division in the eastern part of the city. The largest extent of Mbarara City is dominated by grasslands and other herbaceous vegetation types with low carbon density ranging from 0.96-5.00 t/ha as seen in the north, east and west.

In 2018, there was a noticeable loss of carbon stocks in the Rucece wetland system, along River Rwizi and Nyarubungo hills in Nyakayojo Division while much of the carbon concentration can be observed around Rwimigina forest in the Kakiika Division in the southeastern part of the city. On the other hand, there was a significant loss of vegetation carbon stocks in the central part of the Kakooba and Kamukuzi divisions; northeast in the Biharwe Division and southwest in the Nyakayojo division. In 2023, there was a significant loss of carbon stocks in the central part, northeast around Biharwe and western part while carbon concentration shifted to the tree plantation in Bugashe ward, the southern part of Nyakayojo division and Rwemigina plantation in Kakiika Division, the southeastern part of Mbarara city.

4.4 Land use/cover and carbon stocks predictions for the year 2043 for Mbarara city

This section presents the results for the land use/cover projections for the year 2043 and its effect on carbon stocks within the different green spaces.

4.4.1 Land use/cover predictions

The projected land use/cover results for the year 2043 are presented in Figure 4.7 below.

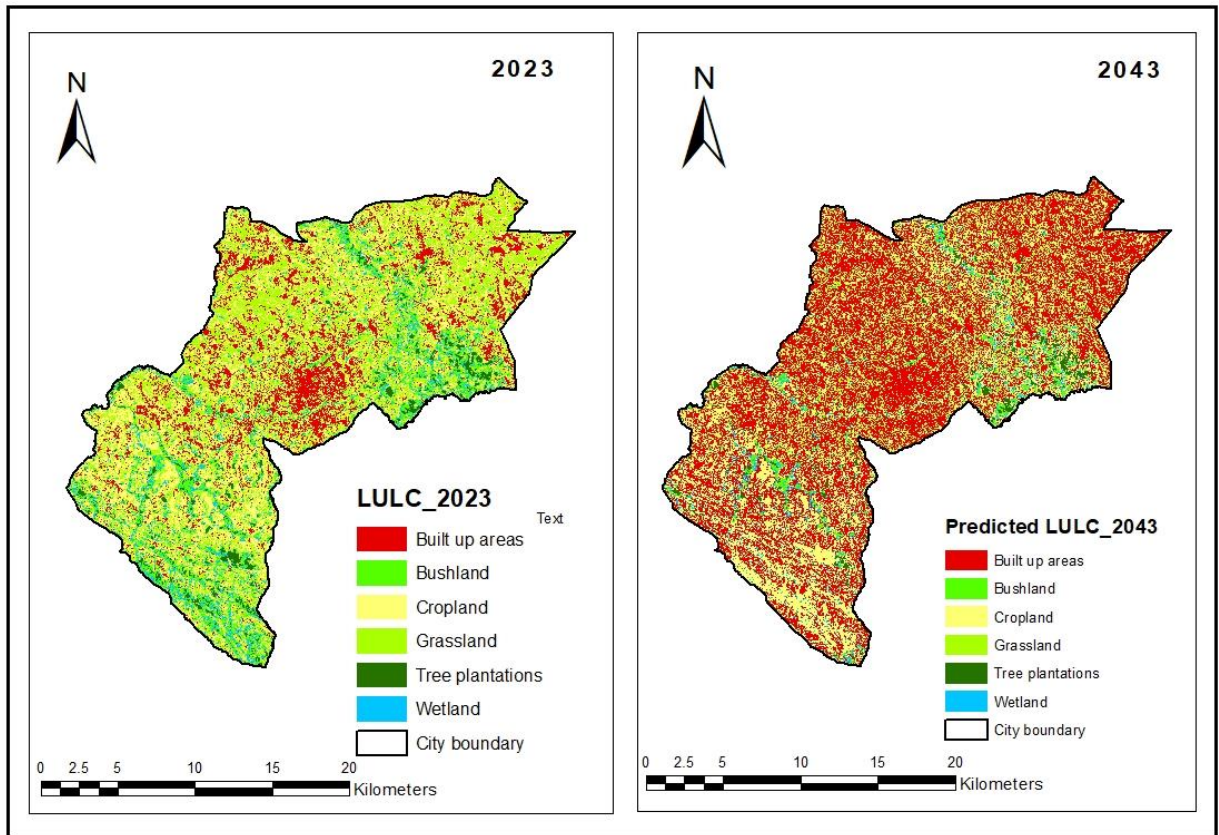


Figure 4. 7: Potential distribution of LULC types of the Mbarara City for the year 2043

The results in Figure 4.7 (for the year 2043) show an overwhelming expansion of the built-up area outwards from the city centre while consuming other land classes, especially grassland, bushland, wetland and tree plantations. In particular, the projection shows both intensification and outward spread of the built-up areas. In the southern and western parts of the Mbarara City in Nyakayojo division, cropland will replace large areas of wetland and grasslands. Further, the simulated land use/cover map shows that wetland and bushland classes will decline in coverage considerably compared to the year 2023, and only persist in the Rucece wetland system in the west, along river Rwizi and the eastern part of the Kakiika division. Likewise, tree cover will reduce and scattered patches will remain in the southeast and the west along river Rwizi while in the city centre, the tree cover will largely convert to bushland.

Further analysis of the land use/cover predictions for the year 2043 showing area and percentage changes was carried out and the results are presented in Table 4.7

Table 4. 7: Land use/cover prediction statistics of Mbarara City

Land use/cover	2023		2043		CHANGE	
	Area (Ha)	%	Area (Ha)	%	Area (Ha)	%
Built up areas	6880	15.6	21830	49.5	14950	33.9
Bushland	4458	10.1	1044	2.4	-3414	-7.7
Cropland	14822	33.6	14398	32.7	-424	-1.0
Grassland	13899	31.5	4251	9.6	-9648	-21.9
Tree plantations	1380	3.1	754	1.7	-626	-1.4
Wetland	2630	6.0	1792	4.1	-838	-1.9

The results presented in Table 4.7 predicted that the overall extent of the built-up area would drastically expand and occupy 49.5% of the total land area covered by the city by 2043 compared to the 15.6% coverage in 2023. This represents an increase in the coverage of the built-up areas of 33.9% in the 20-year projected period. Another significant change is expected in the grassland cover which is projected to decline by 21.9% up from 31.5% (13,899 ha) in the year 2023 to 9.6% (4251 ha) for the year 2043. Similarly, without any interventions, the areal extent of cropland, tree plantation, wetland, and bushland are predicted to decrease by about 1%, 1.4%, 1.9% and 7.7% respectively by 2043.

4.4.2 Carbon stocks predictions for the year 2043

The aboveground carbon stocks for 2043 were predicted based on carbon stock densities of different green spaces for 2023 as the base year. The results are presented in Table 4.8.

Table 4. 8: Carbon stock predictions for Mbarara city

Land use/cover	2023		2043			Change (2023-2043)	
	AGC (t/ha)	Area (Ha)	Gg	Area (Ha)	Gg	Area (Ha)	Gg
Bushland	0.8	4458	3.57	1044	0.84	-3414	-2.73
Grassland	1.04	13899	14.45	4251	4.42	-9648	-10.03
Tree plantations	40.3	1380	55.61	754	30.39	-626	-25.23
Wetland	0.66	2630	1.74	1792	1.18	-838	-0.55
Total		22367	75.37	7841	36.83	-14526	-38.55

The findings presented in Table 4.8 show that total carbon in the green spaces would reduce by 38.55 Gg from 75.37 Gg in 2023 to 36.83 Gg in 2043 without any intervention. Specifically, the greatest carbon losses will be 25.23 Gg in tree plantations and 10.03 Gg in grasslands due to the conversion of 626 Ha of tree plantations and 9,648 Ha of grassland to other land use types. In addition, the predicted loss of 0.55 Gg and 2.73 Gg of carbon is attributed to the conversion of bushland and wetland to other land uses mainly built-up of 838 Ha and 3414 Ha of wetlands and bushland respectively.

4.5 Discussion of results

This section presents the discussion of results according to the study objectives.

4.5.1 The extent of land use/cover changes in Mbarara City between 2013 and 2023

The LULC transitions for the study period (2013-2023) noted both gains and losses for the different LULC types in Mbarara City. The study findings show that grassland and cropland classes covered the largest land area in 2013. However, both classes progressively declined up to the year 2023. Grassland was reduced by 3.3% and 3.6% for the analysis periods 2013-2018 and 2018-2023 respectively. Similarly, cropland experienced a slight increase of 1.3% between the years 2013 and 2018 and a moderate decrease of 5.1% between the years 2018 and 2013. The large area coverage of grassland and cropland in an urban area can be attributed to the recent extension of the city boundaries when it was upgraded from a municipality to a city status in 2020 (Finance, 2007; Nuwagaba, 2022). The persistent decline in grassland and cropland is attributed to the rapid expansion of the built-up areas for the analysis period 2013-2023 which grew from 3.8% to 15.6%

of the total land area in 2023. Moreover, the LULC transitions revealed that the largest land gains for the built-up areas were conversions from grassland and cropland. The findings revealed a substantial expansion of built-up area from 1,682 to 6,880 Ha, a 309% growth in ten years.

This trend is common in the rapidly growing urban areas in the developing parts of the world where rapid population growth is the main driver of urban area expansion (Nero et al., 2020; Puplampu & Boafo, 2021). Similar findings have been observed by the study of Bwanika (2016) which analyzed the temporal and spatial patterns of urban sprawl of Mbarara Municipality for 30 years (1984-1914) and noted an exponential growth of the built-up areas in Mbarara municipality at the expense of vegetation cover. Similarly, a study on Fort Portal Municipality, western Uganda (Wadembere and Kobugabe, 2017) also concluded that the built-up area expanded rapidly between 1998 and 2016 while vegetation coverage was reduced. Several other studies (Abass et al., 2018; Khamchiangta & Dhakal, 2020; Nyongesa et al., 2022; Otunga et al., 2014; Puplampu & Boafo, 2021) have found similar results for cities in Africa and Asia that have experienced exponential growth of built-up areas at the expense of green spaces. In African cities, rapid population growth has been identified as the primary underlying driver of urban land expansion, reflected in the informal and formal residential growth (Nero et al., 2020; Puplampu & Boafo, 2021).

The study further revealed that bushland and wetland land cover types registered fluctuating trends with an overall decline for the entire study period (2013-2023). The slight increase in wetland coverage between 2018 and 2023 was attributed to the NEMA's occasional enforcement of environmental policies and eviction of encroachers. These results are similar to the findings of Bwanika (2016) who investigated spatial and temporal patterns of urban sprawl in Mbarara municipality. The study findings revealed a fluctuating trend in wetland coverage between 1984 and 2014. Wetland degradation in Uganda's urbanized areas has largely been driven by population pressure, the need for livelihood support and political interference (Wetlands Atlas, 2016).

However, the study findings revealed that tree plantations experienced a slight expansion in area coverage from 2.7 to 3.1% between 2013 and 2023. This contrasts with the study finding of Bwanika (2016) which reported declining forest coverage in Mbarara municipality. It further disagrees with the findings of Wadembere and Kobugabe (2017) in Fort Portal municipality,

Nyongesa et al. (2022) in Voi town, Kenya, and Nero et al. (2020) in cities in Sub Sahara Africa which concluded that growth in built-up areas has caused loss of tree cover.

Despite the disagreement in the findings, there are studies in other parts of the world where forest coverage and urban expansion have moved in the same direction. For instance, the study findings of Li et al. (2022) and Zhu et al. (2019) revealed the expansion of forest coverage in the rapidly urbanizing Chinese provinces of Zhejiang and Yunnan respectively, driven by the government policy to boost the ecosystem. On the contrary, in Mbarara city, the tree plantation expansion is on private land largely driven by private economic benefits such as the need for construction materials and wood fuel and therefore might not provide long-term ecosystem services like carbon storage as the case in the Chinese provinces since there is a high possibility of frequent harvests. This is supported by a study by Fitts et al. (2021) which concluded that the probability of forest conversion to other land uses was higher in non-public than public forests. Important to note is that despite the increasing trend in tree plantations between the years 2013 and 2023, the percentage of land area coverage for trees was still low for the year 2023 (3.1%) compared to the findings of Bwanika (2016) in Mbarara municipality in the year 2014 when forest coverage stood at 10% of the land area (Bwanika, 2016; Mbarara City, 2020-2024). This underscores the need for increased tree plantation.

4.5.2 Transition and magnitude of land use/cover change in Mbarara City

The study revealed that all LULC types experienced transitions for the study period. The most significant changes were recorded in grassland, cropland and built-up LULC types. Built-up areas and tree plantations recorded net gains with grassland. Bushland, cropland and wetland experienced net losses. The largest proportion of conversions from grassland and cropland transferred out to built-up areas. The possible explanation for this result is the high population growth rate that results in high demand for residential, commercial and transport facilities (Nero et al., 2020; Puplampu & Boafo, 2021).

Further, there was a notable exchange between grassland and cropland land use/cover types. These results align with the findings of Isunju & Kemp (2016) who reported large area conversions of natural grassland vegetation to cropland and built-up areas in the Nakivubo wetland system.

Another observation was the high instability of green spaces. Notably, tree plantations transferred approximately 64.6% and 53.7% of the land coverage to bushland, grassland, wetland, cropland and built-up areas between the 2013-2018 and 2018-2023 study periods respectively. This implies there is a high level of transition to lower biomass vegetation types and high carbon losses from the vegetation biomass and the soil.

4. 5.2 Carbon stocks in the different urban green spaces

The findings revealed that the contemporary total aboveground carbon stock (for the year 2023) was 75.44 Gg, the largest being stored in tree plantations and grasslands while the least amount was stored in the wetlands and bushland. The large amount of carbon in tree plantations is explained by the large biomass of trees (Chave et al., 2014) while in grassland it is attributed to its vastness. The historical analysis of carbon stocks revealed that total carbon stocks generally increased over the study period from 73.40 Gg to 75.44 Gg largely driven by the areal expansion of tree plantations. Even a slight change in tree cover has a great effect on total carbon because trees have the largest per unit stock density. However, in terms of carbon concentration per unit area, the highest density was found in tree plantations (40.3 t/ha) while it was 0.66 t/ha in wetlands, 0.8 t/ha in bushland and 1.04 t/ha in the grassland.

The carbon density observed in the trees was higher than the carbon density in the African savanna woodlands ranging between 23-32 C t/ha, but much lower than in Tropical High Forest (THF) that range from 72 C t/ha to 114 C t/ha for degraded and well-stocked forests respectively (Nakakaawa et al., 2011). The carbon content in tree plantations depends on the management purpose (Mugagga, 2015). The low carbon density could be explained by the low average DBH (16.5 cm) recorded in most plantations due to the high tree density and young age of most trees because they are frequently harvested to provide building poles. However, the findings on carbon concentration in tree plantation are comparable to the results of a study in the Mount Elgon region, Eastern Uganda by Mugagga (2015) which found a carbon density of 45.22 C t/ha in woodlots/tree plantations for both above and belowground carbon. Woodlots/tree plantations tend to have lower carbon density compared to natural forests and street trees affected by management purposes (Mugagga, 2015). However, green spaces in Kumasi City, Ghana stored an estimated 211 tons of carbon per hectare in the aboveground tree biomass. This is attributed to the abundance of remnant

native tree species that have higher wood-specific gravities and DBH greater than a hundred centimetres (Nero et al., 2020) as opposed to the small-sized trees with average DBH less than thirty centimetres that dominate tree plantations in Mbarara city. According to (Chave et al., 2005), DBH is the most significant biophysical variable affecting tree biomass and carbon stocks.

Grassland was the second most significant carbon sink storing an estimated 14.52 Gg despite having a lower per unit carbon content of 1.04 t/ha. The large carbon content is attributed to the extensive coverage of the grassland which covers 13,899 Ha (31.5%) of land area in the year 2023, as shown in Table 3. Over the study period, there was a consistent decline in the AGC in the grassland due to its reduction in area. These findings support the findings of a study by Li et al. (2022) which noted reduced carbon stocks due to a decline in grasslands in Yunnan province of China between the study years 1990 and 2020.

Wetland stored an estimated 1.74 Gg of carbon with a per unit area carbon content of 0.66 t/ha. Although it was not the focus of this study, wetlands are critical carbon sinks, particularly in the belowground storage as SOC and DOC. The availability and stability of the stored carbon compounds are more valuable than short-term carbon storage (Pant et al., 2015). Thus, the periodical transitions in wetland area coverage affect the effectiveness of carbon storage in the wetland cover in Mbarara City, calling for effective wetland conservation strategies. Bushland stored 0.8 t/ha totaling 3.57 Gg in the year 2023. However, this carbon sink was highly transitional with only 16.7% and 15.7% remaining stable between the study years 2013-2018 and 2018-2023 respectively. This affects long-term carbon storage since the stability of any carbon sink is important for climate change mitigation (Pant et al., 2015).

4.5.3 Land use/cover change and carbon stocks predictions for the year 2043 for Mbarara city

The findings revealed that by the projected year 2043, without any intervention, the built-up area will overwhelmingly expand by 33.9 % to cover 49.5% of the total land area from 15.6% in the year 2023 while grassland will significantly decrease by 21.9%. Tree plantations, bushland and wetland land use/cover were equally predicted to decline. Predicted massive expansion of built-up areas could be attributed to the rapid population growth in the area which would increase the

demand for land to establish residential, social and commercial infrastructures (Nero et al., 2020). It has been projected that future urban growth both in population and land up to 2050 will be greatest in developing countries in Sub-Saharan Africa, in which the study area is located (World Bank, 2021; UN-Habitat, 2022). Moreover, Uganda and Mbarara City have high urban growth rates of approximately 5% per annum (MoLHUD, 2017; UBOS, 2016). The findings of this study are in line with the findings of Taubenböck et al. (2013) which predicted that the built-up areas (grey spaces) would grow from 7.79 km² in 2010 to 18.9 km² signifying a high rate of urban expansion in Uganda putting intense pressure on green spaces that include wetlands.

Similarly, Mohamed & Worku (2020) in Addis Ababa, Ethiopia observed that built-up spaces would continuously expand at the expense of other ecologically valuable LULC types. Likewise, a study by Fitawok et al. (2020) on Bahir Dar City, Ethiopia predicted land use changes for 2025, 2034 and 2045 based on the 2018 situation, and the findings revealed that built-up areas would continue to expand while consuming other land use types. By contrast, a study by Koko et al. (2020) in Zaria City, Nigeria predicted that built-up and vegetation coverage would both increase by the years 2035 and 2050 from the coverage in the year 2020. This was attributed to the government afforestation policy which aimed at converting barren into forest cover. The study findings are consistent with studies in Asian urban areas that future land use/cover change would be dominated by the rapid extension of the urbanized areas and other land use covers would decline, for instance, in Kathmandu city in Nepal (Wang et al., 2020) and Warangal city of India (Satya, 2020).

The study findings further revealed that aboveground carbon stocks in green spaces would reduce by 38.55 Gg by the year 2043 from 75.37 Gg in the year 2023 to 36.83 Gg. The highest losses would come from the conversions of tree plantations (25.23 Gg) and grassland (10.03 Gg) to other land uses. The predicted loss in the aboveground carbon would be explained by the conversion of vegetation cover in the green spaces due to conversion to built-up as shown in Table 9. The massive loss of aboveground carbon in tree plantations compared to the slight decrease in acreage can be explained by the high carbon density in trees because of their large biomass (Houghton et al., 2012). On the other hand, the predicted massive conversion of grassland areas to built-up would lead to the loss of aboveground carbon. Accelerated global land use change has been responsible for the escalation in carbon emissions (Fitts et al., 2021). The findings of this study are comparable

to the findings of similar studies on carbon stock predictions. For instance, in China, urban expansion in developed areas was predicted to be the leading cause of carbon emission between the 2020 and 2030 study period (Feng et al., 2020). Similarly, in the Hunan province of China, the expansion of built-up areas was projected to cause a reduction of 24,597.5 tons of carbon storage between the 2020 and 2040 analysis period due to the loss of vegetation (Zhu et al., 2023).

CHAPTER FIVE

SUMMARY OF RESULTS, CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the summary, conclusion and possible recommendations to various stakeholders based on the study objectives. The recommendations encompass aspects related to policy and future research needs.

5.2 Summary of results

The findings of this study revealed significant land use/cover transitions in Mbarara City over the 10-year study period. The built-up areas and tree plantations consistently expanded, with the expansion in built-up areas being rapid. However, bushland, cropland, grassland and wetland classes generally declined. Further, the study findings revealed substantial transitions in all classes. The built-up areas experienced the highest net gain over the study period at the expense of green spaces like grasslands and wetlands which registered net losses. Grassland experienced the highest net loss. Such transitions point to heightened instability in the land use/cover types and consequently the biomass leading to high carbon fluxes.

An analysis of carbon stocks among the various green spaces revealed that total AGC decreased between 2013 and 2018 but again increased by 2023, with tree plantations and grassland as the major carbon sinks. Notably, the carbon stock in tree plantations steadily increased while in the grassland it significantly decreased over the study period. In addition, there were significant spatial shifts in carbon storage due to land use/cover changes signifying high carbon fluxes, yet, the stability of carbon sinks is critical for long-term carbon storage. These findings underscore the importance of trees in carbon storage and climate mitigation coupled with the need to protect the existing trees and other green spaces and plant more trees to increase carbon sequestration and stability of the carbon sinks.

Furthermore, land use/cover change predictions for the twenty years depict an overwhelming expansion of the built-up areas occupying about 50% of the land area while all the other land use/cover types would decrease by the projected year 2043. Notably, the most significant reduction in land area will affect the grassland and bushland covers that would be converted to grey spaces. Consequently, the aboveground carbon stocks would drastically decrease by over a half following the decrease in green spaces. Specifically, the carbon stock losses would result from the loss of tree cover and grasslands and thus will escalate the carbon emissions in the city. These revelations stress the need for proper urban land use planning and conservation of ecologically sensitive areas to ensure the stability of the carbon sinks for sustainable urbanization.

5.2 Conclusion

The study concluded that in Mbarara city, both the built-up areas and tree plantations consistently expanded spatially between 2013 and 2023 while the other land use/cover types including the green spaces witnessed an overall decline in spatial extent. Despite the historical carbon stock increases caused by the expansion of tree plantations, the increase in carbon stocks was characterized by high carbon fluxes in the area resulting from high levels of transitions across the green spaces, yet the stability of a carbon sink is a fundamental ecological factor for the effective regulation of carbon storage and climate change mitigation. The study findings further suggest that future carbon stocks will reduce significantly as grey spaces expand, emphasizing the urgent need for comprehensive conservation of the ecosystems and urban greening strategies.

5.3 Recommendations

In line with the objectives of this study, several recommendations are offered to lessen and address the effects of land use/cover changes on the loss of urban green spaces and subsequent carbon storage dynamics.

The city authorities should foster an appropriate balance between urban development and environmental protection by enforcing strict implementation of the city physical development plan to ensure the conservation of green spaces, particularly, forested areas and wetlands since they have the highest capacity for carbon sequestration. This involves demarcating the boundaries of

wetlands, public forest lands and all designated green spaces to avoid undue encroachment by private developers and public projects.

There is an urgent need for the city authorities to invest in a wide range of urban greening initiatives such as street tree planting programmes along all roads and the compounds of public institutions within the city and green roofs to increase carbon sequestration and storage potential. In addition, land acquisition, especially, in the hilly areas to plant more trees should be given attention. This can be achieved by establishing public tree nursery beds for each Division and creating mechanisms to increase access to tree seedlings by the local community.

Community-based sensitization to respect the city's physical development plan, and conservation of green spaces, particularly trees and wetlands. The community should be encouraged to protect and even plant more trees on their private premises, especially fruit trees which will provide a wide range of ecosystem benefits including the source of food. Free tree seedlings can be provided.

Further studies should focus on strategies that enhance carbon storage in urban environments to facilitate the transition to more sustainable and resilient ecosystems and attain sustainable development goals.

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Appendices

Appendix I: Field measurement: Ground Inventory Data collection Sheet for trees

Date-----	Name of collector...	
Plot number		
Coordinates	Latitude:	
	Longitude:	
	Altitude	
Environment remarks		
Dominant tree species		
No.	Diameter at breast height (cm)	Height (m)
1		
2		
3		
4		
5		
6		
7		
8		
9		

Appendix II: Field measurement: Ground inventory data collection sheet for herbaceous vegetation

Name of collector		
Date		
Plot number		
Plot dimensions		
Coordinates	Latitude	
	Longitude	
	Altitude	
Vegetation type		
Fresh weight		
Sample weight		

Appendix III: Materials and Equipment for Estimating Aboveground Carbon Stock

No.	Equipment	Function
1	Geographical Positioning System (GPS)	Take coordinates of the sample plots
2	Distance tape measure	Measure plot distance
3	DBH tape measure	Measure the Diameter at Breast Height for trees
4	Clinometer	Measuring tree height
5	Marked sacks/paper bags	For keeping vegetation samples
6	Weighing scale	Measuring fresh weight
7	Panga	Harvesting vegetation
8	Gumboots, umbrella, raincoat	Protection against bad weather

Appendix IV: Measuring carbon

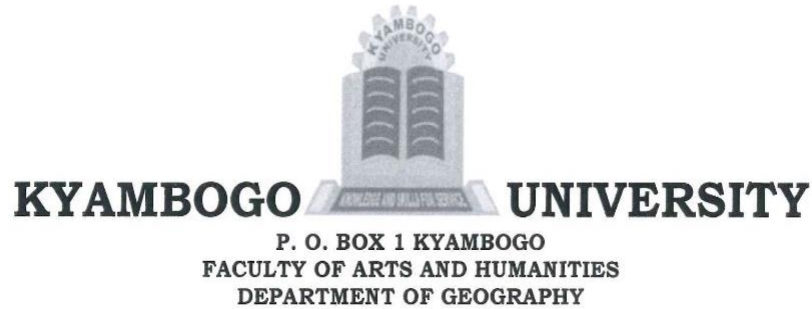


Plate A. 1: Measuring the tree height using a clinometer and diameter at breast height (DBH)



Plate A. 2: Harvesting vegetation for carbon testing (Destructive method)

Appendix V: Field introductory letter



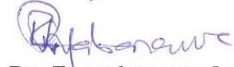
10th November, 2023

**TO WHOM IT MAY CONCERN
MUMPE GODFREY KABAKA
21/U/GMAG/14376/PE**

This is to introduce to you the above named student who is pursuing a Master of Arts in Geography degree course at Kyambogo University. He is in his second and final year and he is supposed to conduct a research study entitled “**Land use/Cover change and its implications on carbon stocks in urban green spaces in Mbarara city**”. His research is under the supervision of Dr. Gabiri Geoffrey and Dr. Loy Gumisiriza Turyabanawe.

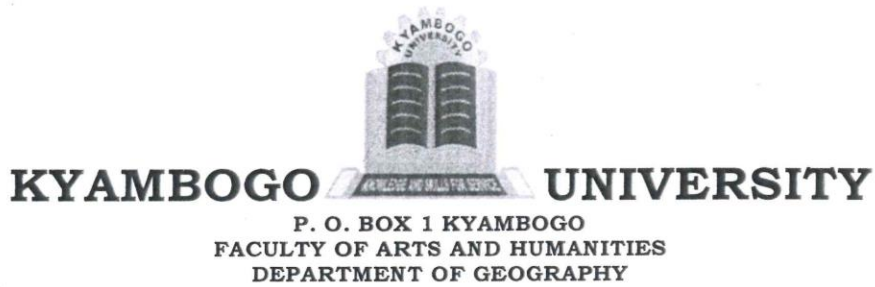
Any assistance accorded to him will be highly appreciated.

Thank you.



Dr. Turyabanawe Loy Gumisiriza
RESEARCH COORDINATOR

Appendix VI: Field data collection acceptance




10th November, 2023

**TO WHOM IT MAY CONCERN
MUMPE GODFREY KABAKA
21/U/GMAG/14376/PE**

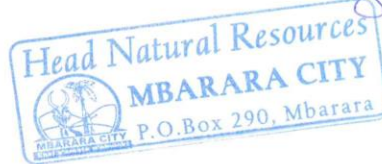
This is to introduce to you the above named student who is pursuing a Master of Arts in Geography degree course at Kyambogo University. He is in his second and final year and he is supposed to conduct a research study entitled **“Land use/Cover change and its implications on carbon stocks in urban green spaces in Mbarara city”**. His research is under the supervision of Dr. Gabiri Geofrey and Dr. Loy Gumisiriza Turyabanawe.

Any assistance accorded to him will be highly appreciated.

Thank you.


Dr. Turyabanawe Loy Gumisiriza
RESEARCH COORDINATOR

*Permission granted
to conduct the academic
research in Mbarara city
in addition to the work
the city is doing with
forestry and environment
J. N. M. P.
26/12/2024*



Appendix VII: Accuracy assessment matrices

	OID	ClassValue	C_1	C_2	C_3	C_4	C_5	C_6	Total	U_Accuracy	Kappa
▶	0	C_1	32	3	1	0	1	1	38	0.842105	0
	1	C_2	3	30	1	0	0	4	38	0.789474	0
	2	C_3	0	1	8	0	0	1	10	0.8	0
	3	C_4	1	1	0	6	0	0	8	0.75	0
	4	C_5	1	0	0	0	2	0	3	0.666667	0
	5	C_6	0	1	0	0	0	2	3	0.666667	0
	6	Total	37	36	10	6	3	8	100	0	0
	7	P_Accuracy	0.864865	0.833333	0.8	1	0.666667	0.25	0	0.8	0
	8	Kappa	0	0	0	0	0	0	0	0	0.716111

	OID	ClassValue	C_1	C_2	C_3	C_4	C_5	C_6	Total	U_Accuracy	Kappa
▶	0	C_1	39	0	0	2	0	0	41	0.95122	0
	1	C_2	1	5	0	1	0	0	7	0.714286	0
	2	C_3	1	1	4	1	0	0	7	0.571429	0
	3	C_4	0	0	0	38	1	0	39	0.974359	0
	4	C_5	0	0	0	0	1	0	1	1	0
	5	C_6	0	0	0	1	0	4	5	0.8	0
	6	Total	41	6	4	43	2	4	100	0	0
	7	P_Accuracy	0.95122	0.833333	1	0.883721	0.5	1	0	0.91	0
	8	Kappa	0	0	0	0	0	0	0	0	0.862595

	OID	ClassValue	C_1	C_2	C_3	C_4	C_5	C_6	Total	U_Accuracy	Kappa
▶	0	C_1	48	1	6	0	1	1	57	0.842105	0
	1	C_2	2	7	0	0	0	0	9	0.777778	0
	2	C_3	1	0	22	0	0	0	23	0.956522	0
	3	C_4	0	0	1	4	0	0	5	0.8	0
	4	C_5	0	0	1	0	3	0	4	0.75	0
	5	C_6	0	0	0	0	0	2	2	1	0
	6	Total	51	8	30	4	4	3	100	0	0
	7	P_Accuracy	0.941176	0.875	0.733333	1	0.75	0.666667	0	0.86	0
	8	Kappa	0	0	0	0	0	0	0	0	0.777389

Appendix VIII: Transition matrix for 2013 to 2023

Sum of Area (ha)	Column Labels						
Row Labels	Built up areas	Bushland	Cropland	Grassland	Tree plantations	Wetland	Grand Total
Built up areas	1058.24	21.46	266.90	199.57	6.27	13.51	1565.95
Bushland	468.47	998.29	1060.23	1403.75	304.46	598.10	4833.29
Cropland	1042.72	1759.84	7097.77	5386.58	364.46	1002.33	16653.70
Grassland	4241.35	485.38	5681.66	6278.99	132.90	213.73	17034.01
Tree plantations	13.07	432.17	110.25	109.78	407.06	170.82	1243.15
Wetland	55.21	758.25	603.02	517.26	164.61	630.68	2729.03
Grand Total	6879.06	4455.38	14819.83	13895.93	1379.77	2629.17	44059.14