UNIVERSITY of RWANDA

College of Science and Technology

School of Architecture and Built Environment

MSc in Geo-Information Science for Environment and Sustainable Development

Evaluating the Effects of Urban Expansion on Forest Cover Degradation: A Case Study of Rubavu City, Rwanda

Thesis submitted to the University of Rwanda: College of Science and Technology in partial fulfilment of the requirements for the award of the Degree of Master of Science in Geo-Information for Environment and Sustainable Development.

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October, 2024

Declaration

I, Eustache AKUZWE, do hereby declare that this thesis is my original work, and has not been previously submitted or examined for any award of any degree at University of Rwanda or any other University.

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Approval

It is hereby confirmed that this thesis entitled **"*Evaluating the Effects of Urban Expansion on Forest Cover Degradation: A Case Study of Rubavu City, Rwanda*"** submitted by Eustache AKUZWE, was assessed in relation to the fulfilment of the requirements for the award of the Degree of Master of Science in Geo-Information for Environment and Sustainable Development, in the School of the of Architecture and Built Environment.

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Acknowledgments

First and foremost, I want to thank the Almighty God, the giver of life and the protector, for his unconditional love and grace that enabled me to complete this work successfully

Also, my deepest appreciation and heartfelt special thanks go to my supervisors Assoc Prof. Aime TSINDA, Dr Adrien UWAMAHORO and Mr. Hyacinthe NGWIJABAGABO for their guidance, moral support and valuable contribution during the preparation of this dissertation. They spent precious time to give me regular advice and corrections to document from the very beginning to end. The result of this study is from their expertise and professional assistance. May God bless him abundantly!

Additionally, special thanks to my colleagues and members of my cohort together with other students, faculty members and staffs from, I say thank you for making my stay in University of Rwanda-College of Science and Technology (UR-CST), and my life at University was a pleasant and memorable.

Finally, I want also to convey special thanks my wife, my mother, my brother and sisters, all relatives, and friends for their love, care and support. They were my source of encouragement and motivation throughout this work.

Eustache AKUZWE

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Abbreviations and Acronyms

AOI: Area of Interest

CBD: Convention on Biological Diversity

CHIRPS: Climate Hazards Group InfraRed Precipitation with Station Data

DPSIR: Driver-Pressure-State-Impact-Response

EROS: Earth Resources Observation and Science

ES: Ecosystem Services

ESV: Ecosystem Services Valuation

ETM+: Enhanced Thematic Mapper Plus

FAO: Food and Agriculture Organization

GDP: Gross Domestic Product

GEE: Google Earth Engine

GGGI: Global Green Growth Institute

GIS: Geographic Information System

GoR: Government of Rwanda

GPS: Global Positioning System

IPCC: Intergovernmental Panel on Climate Change

Km^2: Square Kilometer

LCLU: Land Cover/Land Use

LST: Land Surface Temperature

LULC: Land Use and Land Cover

MLC: Maximum Likelihood Classifier

MoE: Ministry of Environment

NDBI: Normalized Difference Built-up Index

NDVI: Normalized Difference Vegetation Index

NGOs: Non-Governmental Organizations

NISR: National Institute of Statistics of Rwanda

NLUMP: National Land Use and Development Master Plan

NST: National Strategy for Transformation

NST1: National Strategy for Transformation (Phase 1)

OLI/TIRS: Operational Land Imager and Thermal Infrared Sensor

PFM: Participatory Forest Management

PHC5: 5th Rwanda Population and Housing Census

PSTA 4: Strategic Plan for Agriculture Transformation (Phase 4)

QGIS: Quantum Geographic Information System

REMA: Rwanda Environment Management Authority

RFA: Rwanda Forestry Authority

ROI: Region of Interest

RUSLE: Revised Universal Soil Loss Equation

SDGs: Sustainable Development Goals

SPI: Standardized Precipitation Index

T(cs): Total Corrected Samples

T(s): Total Sample

TM: Thematic Mapper

UN: United Nations

UN-Habitat: United Nations Human Settlements Programme

UNDESA: United Nations Department of Economic and Social Affairs

USD: United States Dollar

USGS: United States Geological Survey

UTM: Universal Transverse Mercator

VC: Value Coefficient

WGS: World Geodetic System

WRI: World Resources Institute

Abstract

This study investigates the impacts of urban expansion on forest cover in Rubavu City from 2000 to 2020 and proposes evidence-based mitigation strategies to address the resulting environmental challenges. Using remote sensing data and land cover analysis, the research employed a spatio-temporal approach to assess changes in forested and non-forested areas over two decades. The analysis revealed a significant decline in forest cover, with forested areas decreasing from 20.17 sq.km (41.51%) in 2000 to 9.66 km^2 (19.88%) by 2020. Concurrently, non-forested areas expanded from 28.42 km^2 (58.49%) to 38.93 km^2 (80.12%) during the same period. The reduction in forest cover was accompanied by a notable decline in the value of ecosystem services, including erosion control and climate regulation. The total ecosystem services value decreased from USD 19,901.54 per hectare in 2000 to USD 9,531.43 per hectare by 2020. Interviews with local officials corroborated these findings, highlighting increased urban temperatures and heightened risks of landslides and floods as direct consequences of deforestation. Based on these findings, the study recommends implementing comprehensive land use planning, promoting reforestation efforts, and enhancing urban green spaces. These measures aim to balance development with environmental sustainability, mitigate the adverse effects of deforestation, and restore the ecological and economic benefits of forest ecosystems in Rubavu City. Future research should focus on long-term monitoring of forest dynamics and ecosystem service changes to guide sustainable urban development. The integration of advanced remote sensing technologies and ground-based surveys will be crucial in assessing ongoing impacts and informing effective management strategies.

Keywords: Urban Expansion, Forest loss, GIS, Remote Sensing, Ecosystem Services, Reforestation, Rubavu City.

Chapter One: Introduction

1.1. Background

Urbanization is advancing at an unprecedented rate globally, and rapid urbanization in developing countries is a major concern for policymakers and urban planners (Simkin et al., 2022). By 2050, it is projected that 70% of the world's population will reside in urban areas (He et al., 2021; Kii, 2021). At present, a majority of the world's inhabitants reside in urban areas, marking the most significant surge of urban growth in history (UN-Habitat, 2016). This increase is largely taking place in Africa and Asia, especially in less populated urban areas that frequently lack the capacity to adequately handle such swift transformations (UN-Habitat, 2020).

In developing countries, urbanization is often driven by migration from rural areas to cities, as people seek improved living standards (Sakketa, 2023). This migration is influenced by both pull and push factors, including the availability of employment opportunities, quality of life, and economic stability (Urbański, 2022). The allure of an urban lifestyle and the attractions of city life further contribute to the influx of people, resulting in both temporary and permanent migration to urban areas (UNDESA, 2018; Woetzel, Remes, & Law, 2016; World Bank Group, 2020).

Urbanization has functioned as a facilitator for sustainable development, driving modernization, economic growth, and overall progress (Ye et al., 2021). It was found that urbanization, which accounts for more than 80% of the worldwide GDP, has the capacity to promote sustainable development by boosting productivity and innovation, as long as it is managed properly (UN-Habitat, 2017a). However, the fast rate and extensive scope of urban development present considerable challenges, especially those of an environmental nature (Seifollahi-Aghmiuni et al., 2022). Specifically, deforestation, urbanization and related human activities have traditionally contributed to the reduction of forested areas and the fragmentation of the remaining forests into smaller, isolated sections (Ortiz et al., 2021). According to Ahmed (2020), urban resilience and sustainability are critical components in addressing the challenges posed by rapid urbanization, particularly in megacities of the Global South. The author argues that as cities expand, they must adapt to environmental changes while ensuring social equity and economic growth.

Africa has undergone substantial urbanization over the past two decades, with 40.4% of its population living in cities (Chatterjee et al., 2020). For example, in Ghana, remote sensing data

shows that urban built-up areas have increased from 51.1% to 83.79% between 1991 and 2018, leading to a reduction in forest cover from 41% to 15% over 27 years (Wang & Kintrea, 2021). In Eastern Africa, urbanization is fueled by population growth, rural-urban migration, and economic development (Sakketa, 2023). This region is experiencing rapid urban expansion, resulting in the loss of forested areas (Li et al., 2022). The impacts of urban expansion on forest cover in Eastern Africa are particularly concerning due to the region's rich biodiversity, fragile ecosystems, and the dependence of local communities on forest resources (Tekalign et al., 2018).

Rwanda, with an urbanization rate of about 18%, is experiencing one of the fastest rates of urban population growth at 4.5% annually, far exceeding the global average of 1.8% (Nzeyimana, 2021). Kigali, the capital city, and secondary cities such as Muhanga, Huye, Rusizi, Rubavu, Nyagatare, and Musanze, are undergoing significant urban growth and expansion (Niyonzima, 2020).

The expansion of urban areas has a profound impact on urban forest ecosystems and the services they provide (Puplampu & Boafo, 2021). Urban forests play a crucial role in regulating floods, reducing air pollution, moderating temperatures, and enhancing biodiversity (O'Brien et al., 2022). They also provide recreational spaces, improve mental health, and contribute to the overall quality of life in urban environments (Mouratidis, 2021). However, urban expansion often leads to the degradation of these vital ecosystems, resulting in diminished ecosystem services. For instance, the reduction in forest cover can exacerbate urban flooding, as trees and vegetation that absorb rainfall are removed, leading to increased runoff and higher flood risks (Qin, 2020). The loss of urban forests also contributes to the urban heat island effect, where cities experience higher temperatures than their rural surroundings due to the reduction in natural cooling provided by trees (Gunawardena et al., 2017). Additionally, the decline in air quality due to reduced vegetation cover can have significant health implications for urban residents (Diener & Mudu, 2021).

This study aims to evaluate the effects of urban expansion on forest cover degradation in Rubavu City, Rwanda. By analyzing trends in urban growth and forest cover change over the past three decades, this research seeks to provide insights into the complex interplay between urbanization and environmental sustainability in Rwanda. The study will utilize advanced geospatial techniques and remote sensing data to quantify changes in forest cover and assess the impacts of urban expansion on local ecosystems. Ultimately, this research will contribute to the broader discourse on sustainable urban planning and forest conservation in rapidly urbanizing regions.

Understanding these dynamics is essential for developing strategies to mitigate the adverse effects of urbanization on forest ecosystems and the essential services they provide.

1.2. Problem Statement

Rubavu City, a rapidly growing secondary city in Rwanda, is encountering significant challenges related to urban expansion and its impact on forest cover. As part of Rwanda's decentralization strategy to alleviate pressure on Kigali the country's primary economic and industrial hub which houses over 70% of Rwanda's industrial activities, about 50% of wholesale businesses, and 70% of banking services (Nduwayezu et al., 2021). Rubavu was designated as a key secondary city. This strategy aims to transform the country's economic geography, balance regional development, and mitigate urban sprawl (World Bank Group, 2017; REMA, 2017).

Rubavu has experienced an urbanization rate of 42% as of 2020, significantly surpassing the national average of 18% (IPAR, 2020; Republic of Rwanda, 2017). This rapid growth is attributed to Rubavu's strategic location as an international gateway city near the border with Goma in the Democratic Republic of Congo (DRC), its role as a central hub for tourism and industry, and its bustling trade border known as "La Petite Barrière" (Rwanda Dispatch, 2023).

However, the accelerated urbanization in Rubavu has resulted in substantial land cover changes and increased pressure on natural resources. The city's growth has exceeded its planning capacity, leading to high population densities, land scarcity, and fragmentation into small, uneconomical plots. These issues have caused widespread encroachment into forested areas, leading to significant deforestation. Between 2001 and 2022, Rubavu lost approximately 919 hectares of tree cover, which corresponds to a 5.6% decrease since 2000 (Global Forest Watch, 2022).

This rapid urban expansion and its impact on forest cover present critical challenges. Current research lacks detailed analysis on how urban growth specifically affects forest ecosystems in Rubavu. There is an urgent need for a comprehensive study to understand these effects and develop effective strategies for mitigating environmental impacts.

This research aims to fill this gap by evaluating the effects of urban expansion on forest cover degradation in Rubavu City. It will provide insights into the spatial and temporal dimensions of

forest loss, assess the direct and indirect impacts of urbanization, and propose evidence-based recommendations for sustainable urban planning and forest management.

By addressing these issues, the study seeks to inform policymakers, urban planners, and stakeholders about the environmental consequences of unchecked urban expansion and support the development of strategies that balance urban growth with environmental conservation. This research will also contribute to broader efforts to manage urbanization sustainably and protect critical forest resources.

1.3. General Objective

To assess the impact of urban expansion on forest cover degradation in Rubavu City from 2000 to 2020 using GIS and Remote Sensing techniques.

1.3.1. Specific Objectives

- To analyse the trends and patterns of urbanization and urban expansion in Rubavu City from 2000 to 2020.
- To examine the spatio-temporal changes in forest cover within Rubavu City over the same period.
- To investigate the impacts of urban expansion on forest ecosystem services in Rubavu City and propose evidence-based mitigation strategies to address these environmental challenges.

1.3.2. Research Questions

- What are the trends and patterns of urbanization and urban expansion in Rubavu City from 2000 to 2020?
- How has forest cover in Rubavu City changed spatially and temporally from 2000 to 2020?
- What are the impacts of urban expansion on forest ecosystem services, and what evidence-based mitigation strategies can be proposed to address these environmental challenges?

1.4. Motivation of the Research

This research focuses on Rubavu, a secondary city chosen for its distinctive characteristics that make it an ideal location for studying urban growth and its impact on forest cover. Rubavu has experienced a notably high rate of urbanization compared to other secondary cities in Rwanda, with an urbanization rate of 42% (IPAR, 2020), significantly higher than the national average of

18% (Republic of Rwanda, 2017). This rapid urban growth is largely attributed to Rubavu's strategic position as an international gateway city near the border with Goma in the Democratic Republic of Congo (DRC). Additionally, Rubavu serves as a central hub for tourism and industry, further driving its urbanization. The city is also home to a bustling trade border known as "La Petite Barrière" (Rwanda Dispatch, 2023).

Data from Global Forest Watch reveal that Rubavu lost 919 hectares of tree cover between 2001 and 2022. This significant deforestation highlights the city's importance as a case study for analyzing the effects of urban expansion on forest cover. The research aims to provide critical insights into how urban development contributes to forest loss through activities such as clearing land for housing, road construction, and town expansion.

The findings of this study are expected to be valuable to local administrators and policymakers. By understanding the impact of urbanization on forest cover, stakeholders can develop and implement effective forest management and urbanization policies. These policies would focus on promoting orderly town development and urban densification while minimizing deforestation. Additionally, the research is intended to enhance the broader body of knowledge, inform office administrators, and raise public awareness about the importance of forest protection.

Furthermore, this study aims to raise awareness among urban planners, policymakers, decision-makers, and the general public about the adverse effects of urban expansion on forest resources. By doing so, it seeks to ensure the sustainable use of forest resources, balancing urban development with environmental conservation. The research also provides a foundation for future studies, offering a starting point for other researchers interested in exploring similar topics.

1.5. Scope of the study

Even though there are the largest part of country that was previously covered by forest and later being affected by different factors including urban expansion, this research was only limited in terms of content, geographical and time scope.

1.5.1. Content scope

In terms of content scope, this research mainly focused on the impact of urban expansion and forest cover. Urban expansion in context of this research is the physical enlargement of built-up urban areas. The forests subjected to numerous definitions but for purpose of our research, forest is

minimum land area of 0.05-1 ha with tree crown covers more than 10-30% and tree height of 2-5m at maturity excluding the stand-alone trees that were planted for agricultural purpose, like fruits trees, also include the young stands trees with height of 5m that did not reach the crown density of 10% but expected to reach it (FAO, 2006).

1.5.2. Geographical scope

For the geographical scope, this study specifically considered Rubavu city located in Rubavu district of the Western Rwanda. The sectors of Gisenyi, Rubavu, Rugerero, Nyakiliba, Nyanyumba, and Nyundo were considered as part of Rubavu city.

1.5.3. Time scope

Regarding the time scope, the research considered the data ranging from 2000 to 2020. This research timeline was chosen by the researcher to better indicate how much urban expansion practices contributed to changes on forest cover within the study area (Rubavu city). This period (20 years) is enough to facilitate the policy makers and urban dwellers to understand changes recorded and ways of adaptation as well

1.6. Conceptual Framework

The conceptual framework for this research illustrates the relationships between independent variables (urban growth), dependent variables (forest cover), and intervening variables (urbanization and forest management policies). Typically, an increase in built-up areas and population density leads to a reduction in forested land as more space is needed for housing, infrastructure, and amenities. This often results in the clearing of forests to accommodate urban growth.

The framework also considers the role of intervening variables such as urbanization policies and forest management practices. Effective urbanization policies, such as promoting vertical growth (high-rise buildings) rather than horizontal expansion, can help mitigate the negative impacts of urban growth on forest cover. Additionally, robust forest management policies can ensure that urban expansion is balanced with forest conservation efforts. For example, policies could include the establishment of urban green spaces or initiatives for reforestation in cleared areas.

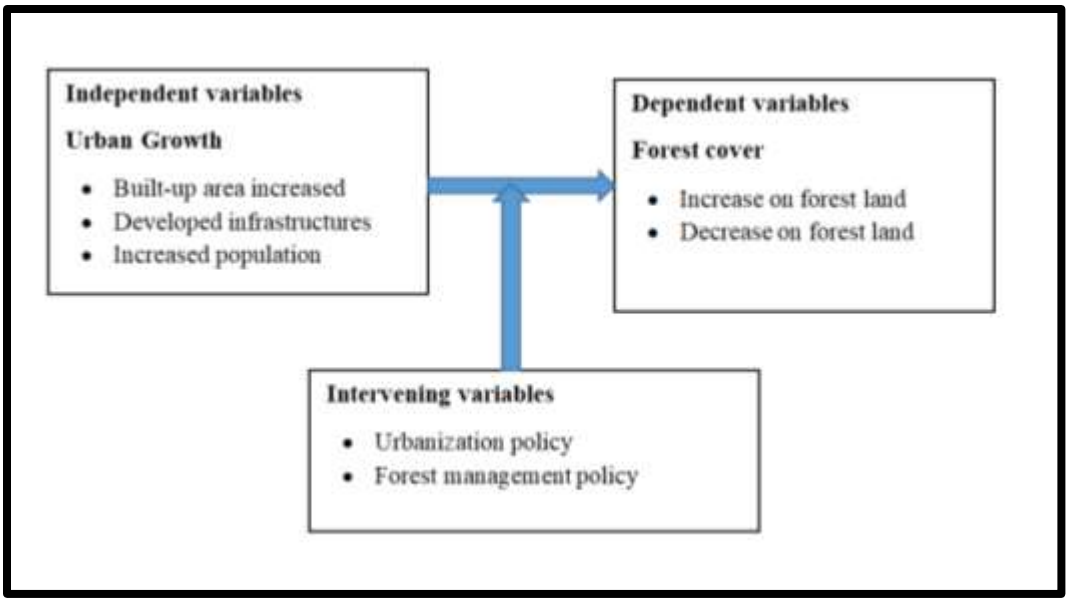

Figure 1: Conceptual framework

1.7. Organization of the study

This research is organized into five chapters. Chapter One, *General Introduction*, provides an overview of the study, including the background, objectives, research questions, and the significance of the research. Chapter Two, *Literature Review*, explores key concepts related to urban expansion and forest cover within urban areas, drawing from various global studies with a specific focus on the study area. Chapter Three, *Research Methodology*, describes the study area and outlines the methods and techniques employed throughout the research. Chapter Four, *Results and Discussion*, presents the findings of the study and offers a detailed analysis and discussion of the results. Finally, Chapter Five, *Conclusion and Recommendations*, summarizes the research, provides conclusions, and offers recommendations based on the study's findings.

Chapter two: Literature review

2.0. Introduction

This literature review synthesizes research on the impact of urban expansion on forest cover degradation, focusing on Rubavu City. By analysing relevant studies, it identifies key trends, challenges, and opportunities at the intersection of urbanization and forest management. The review also discusses the broader implications of forest cover degradation on ecosystem integrity, biodiversity conservation, and local community well-being.

2.1. Historical Context of Urban Expansion

Urbanization has been a defining characteristic of human civilization, with cities emerging as centers of trade, culture, and governance (Weiqi Zhou , Sai Zhang , Wenjuan Yu, 2017). The history of urban expansion dates back to ancient times, where early settlements gradually evolved into complex urban centers (Morshed et al., 2017). Over the centuries, urbanization has accelerated, driven by industrialization, technological advancements, and population growth (UN DESA, 2018). The pace and scale of urbanization have varied across regions, with some areas experiencing rapid growth, while others have seen more gradual development (Chitrakar et al., 2016).

During the 20th century, urbanization became a global phenomenon, with cities expanding rapidly in both developed and developing countries (Jedwab & Vollrath, 2015). This period saw significant changes in urban form and structure, including the rise of suburbanization, the development of megacities, and the increasing influence of globalization on urban growth patterns (Black, 1996). The expansion of cities during this time laid the foundation for many of the challenges and opportunities that characterize modern urbanization (UN-Habitat, 2014).

2.1.1. Early Urbanization and Its Impacts

The early stages of urbanization were often marked by the concentration of population and economic activities within city centers (Taubenböck et al., 2012). As cities grew, they began to exert a significant influence on surrounding rural areas, leading to changes in land use, resource allocation, and social structures (Black, 1996; Liang et al., 2019). In many cases, this expansion

was driven by the need for more housing, infrastructure, and services to accommodate growing populations (Angel et al., 2005). However, the rapid pace of urban growth also led to various challenges, including overcrowding, pollution, and inadequate infrastructure (UN DESA, 2018).

The impacts of early urbanization were not limited to the physical environment; they also had profound social and economic consequences. The concentration of wealth and resources in urban areas often exacerbated social inequalities, leading to the marginalization of certain groups and the creation of informal settlements (Chitrakar et al., 2016). Additionally, the expansion of cities often came at the expense of agricultural land, forests, and other natural resources, leading to environmental degradation and the loss of biodiversity (UN-Habitat, 2014; Maniraho et al., 2021).

2.1.2. Evolution of Urban Expansion Patterns

As cities continued to grow throughout the 20th and 21st centuries, new patterns of urban expansion began to emerge (L. Li et al., 2014). One of the most notable trends was the shift from compact, high-density development to low-density, sprawling urban forms (Tsai, 2005). This change was driven by various factors, including the increasing availability of automobiles, changes in housing preferences, and the decentralization of economic activities (Seto et al., 2012). The result was the spread of urban areas into surrounding rural regions, often leading to the fragmentation of landscapes and the blurring of urban-rural boundaries (Zubair et al., 2015).

The evolution of urban expansion patterns also reflected broader changes in global economic and social structures. For example, the rise of the knowledge economy and the globalization of trade and finance have significantly influenced the spatial organization of cities, leading to the emergence of new urban forms, such as edge cities, technopoles, and global cities (Gao & O'Neill, 2020). These changes have had profound implications for urban planning and governance, as cities grapple with the challenges of managing growth, ensuring sustainability, and promoting social equity (UN-Habitat, 2014).

2.2. Modern Drivers of Urban Expansion

2.2.1. Economic and Demographic Factors

Economic growth and demographic changes are among the most significant drivers of modern urban expansion (Tao & Ye, 2022). As cities become centers of economic activity, they attract investment, businesses, and workers, leading to the continuous expansion of urban areas (Jedwab & Vollrath, 2015; Seto et al., 2012). Population growth, particularly in developing countries, has also played a critical role in driving urban expansion, as millions of people migrate to cities in search of better opportunities and living conditions (UN DESA, 2019). This influx of people has led to the rapid expansion of urban areas, often outpacing the capacity of local governments to provide adequate infrastructure and services (Cobbinah & Aboagye, 2017).

In addition to population growth, economic development has also influenced the pace and pattern of urban expansion. As cities grow economically, they often experience increased demand for housing, commercial space, and infrastructure, leading to the outward spread of urban areas (Gao & O'Neill, 2020). However, this growth can also exacerbate social inequalities and environmental degradation, particularly in regions where urban planning practices are inadequate or non-existent (Seto et al., 2012; UN DESA, 2019).

2.2.2. Socioeconomic and Cultural Drivers

Socioeconomic and cultural factors are also crucial drivers of urban expansion. Changes in lifestyle preferences, housing demands, and consumption patterns have significantly influenced the pace and pattern of urban growth (Cobbinah & Aboagye, 2017). For example, the increasing preference for suburban living, driven by desires for larger homes, more green space, and improved quality of life, has contributed to the expansion of cities into surrounding rural areas (G. Li & Li, 2019). Additionally, cultural factors, such as shifts in family structures, social norms, and values, have also played a role in shaping urban growth patterns (Surya et al., 2020).

Furthermore, the migration of people from rural to urban areas, often driven by economic, social, and environmental factors, has significantly contributed to the expansion of cities (Surya et al., 2020; Seto et al., 2012). This rural-urban migration is particularly pronounced in developing

countries, where rapid population growth and limited economic opportunities in rural areas have led to the continuous influx of people into cities (Cobbinah & Aboagye, 2017). The resulting urban expansion has had far-reaching implications for social equity, environmental sustainability, and urban governance (Liang et al., 2019; UN-Habitat, 2014).

2.3. Characteristics and Patterns of Urban Expansion

2.3.1. Low-Density Development and Urban Sprawl

Low-density development, often referred to as urban sprawl, is one of the most prominent characteristics of modern urban expansion (Artmann et al., 2019). This pattern of growth is typically characterized by the spread of residential, commercial, and industrial areas into surrounding rural regions, often at the expense of agricultural land and natural ecosystems (Gomes, 2020).Urban sprawl is associated with various negative impacts, including increased traffic congestion, higher energy consumption, and the loss of open space (Surya et al.2021). Additionally, low-density development can strain infrastructure and public services, leading to inefficiencies in the provision of transportation, water, and sanitation (Carrilho & Trindade, 2022)

Urban sprawl is also closely linked to changes in lifestyle preferences and housing demands, as more people seek larger homes, more green space, and a suburban lifestyle (Cobbinah & Aboagye, 2017). This trend has led to the expansion of cities into surrounding rural areas, often resulting in fragmented urban landscapes and the blurring of urban-rural boundaries (Zubair et al., 2015). The environmental consequences of urban sprawl are significant, including the loss of biodiversity, increased air and water pollution, and the degradation of ecosystems (Zipperer et al., 2020).

2.3.2. Leapfrogging, Strip Development, and Fragmentation

Leapfrogging occurs when new developments are established at a distance from existing urban areas, leaving undeveloped land in between (Glockmann et al.2022; Kinuthia et al., 2022). This pattern can lead to the inefficient use of land and infrastructure, as well as increased transportation costs and environmental degradation (Surya et al.2021). Strip development, on the other hand, involves the linear expansion of urban areas along major transportation routes, often leading to traffic congestion and the loss of open space (Wen et al., 2020).

Fragmentation refers to the breaking up of continuous urban areas into smaller, isolated patches of development (Kowe et al.2021). This pattern can result in the loss of agricultural land, increased habitat fragmentation, and the disruption of ecological processes (Jin et al., 2020; Simkin et al.2022). Fragmented urban landscapes also pose challenges for urban planning and governance, as they make it more difficult to coordinate infrastructure development, public services, and environmental protection (Huang et al., 2021). The combination of these patterns of urban expansion can have significant social, economic, and environmental consequences, particularly in rapidly growing cities (Zipperer et al., 2020).

2.3.3. Blurring of Urban-Rural Boundaries

The expansion of urban areas into surrounding rural regions often leads to the blurring of urban-rural boundaries (Balta & Atik, 2022). This phenomenon is characterized by the gradual integration of urban and rural areas, with rural landscapes being transformed into suburban or peri-urban areas (Zubair et al., 2015).

The blurring of these boundaries can have significant implications for land use, governance, and environmental sustainability (Mohamed et al., 2020). In many cases, the expansion of cities into rural areas leads to the loss of agricultural land, the fragmentation of natural habitats, and the disruption of traditional rural livelihoods (Güneralp et al.2020). The blurring of urban-rural boundaries is also associated with the emergence of new forms of urbanization, such as exurban development, which involves the spread of low-density residential and commercial areas into rural regions (Gao & O'Neill, 2020). This type of development is often characterized by a mix of urban and rural land uses, leading to complex and fragmented landscapes (Aguilar et al., 2022). The challenges associated with managing these landscapes are significant, as they require the coordination of land use planning, infrastructure development, and environmental protection across multiple jurisdictions (Gomes, 2020).

2.4. Environmental Impacts of Urban Expansion

2.4.1. Deforestation and Forest Degradation

One of the most significant environmental impacts of urban expansion is deforestation and forest degradation (Tilahun et al., 2022). As cities expand into surrounding rural areas, forests are often cleared to make way for new residential, commercial, and industrial developments (Farid et al.2022). This loss of forest cover has far-reaching consequences for biodiversity, ecosystem services, and climate regulation (Pandey & Ghosh, 2023). Deforestation also contributes to soil erosion, reduced water quality, and the loss of carbon sequestration capacity, all of which have significant implications for environmental sustainability (Kumar et al.2022).

The expansion of urban areas into forested regions is often driven by economic and demographic factors, such as population growth, increasing demand for land, and the need for infrastructure development (Mahtta et al.2022). However, the environmental consequences of deforestation are often overlooked in the pursuit of short-term economic gains (Masolele et al.2024). The loss of forests not only threatens biodiversity but also undermines the ability of ecosystems to provide essential services, such as water purification, air quality regulation, and climate moderation (Kattel, 2022)

2.4.1.1. Impact on Rural and Indigenous Communities

The loss of forests due to urban expansion has profound socioeconomic implications, particularly for rural and indigenous communities (Hofflinger et al., 2021; Vijayan et al.2021; Tilahun et al., 2022).These communities often rely on forests for their livelihoods, including agriculture, hunting, gathering, and the harvesting of non-timber forest products (Alule et al.2023). The expansion of urban areas into forested regions can lead to the displacement of these communities, the loss of traditional knowledge and practices, and the disruption of cultural ties to the land (Daunt et al., 2021). Furthermore, the loss of forests can undermine food security, as agricultural lands are converted into urban areas, reducing the availability of arable land (Gao & O'Neill, 2020).

The socioeconomic impacts of forest loss are often exacerbated by social inequalities, as marginalized communities are disproportionately affected by the negative consequences of urban

expansion (Zubair et al., 2015; Yussif et al., 2023). The displacement of rural and indigenous communities can lead to the loss of cultural heritage, social cohesion, and economic opportunities (Onyebueke et al.2020). Furthermore, the expansion of urban areas into forested regions can exacerbate conflicts over land and resources, as different groups compete for access to limited natural resources (Anderson et al., 2022).

2.4.1.2. Economic Consequences and Social Inequality

The economic consequences of forest loss due to urban expansion are significant, particularly in regions where forests play a critical role in local economies (Lacerda et al.2021). The conversion of forests into urban areas can lead to the loss of valuable timber resources, the decline of eco-tourism, and the disruption of ecosystem services that support agriculture, fisheries, and other industries (Mishra et al.2022; Nowak & Greenfield, 2020). Additionally, the loss of forests can increase the vulnerability of local communities to environmental hazards, such as floods, landslides, and droughts, which can have severe economic and social consequences (Gao & O'Neill, 2020; Fremout et al.2020).

Social inequality is often exacerbated by the loss of forests, as marginalized communities bear the brunt of the negative impacts of urban expansion (Castro, 2023). The displacement of rural and indigenous communities, the loss of traditional livelihoods, and the degradation of natural resources all contribute to social and economic inequalities (Zubair et al., 2015; Dawson et al.2023). The failure to address these inequalities can lead to social unrest, increased poverty, and reduced resilience to environmental and economic shocks (Ahmed, 2020). Addressing the socioeconomic implications of forest loss requires a comprehensive approach that integrates social equity, environmental sustainability, and economic development (Li et al.2023).

2.4.2. Loss of Biodiversity and Ecosystem Services

Urban expansion has significant implications for biodiversity and ecosystem services (Simkin et al.2022). The conversion of natural habitats into urban areas leads to the loss of species, the disruption of ecological processes, and the degradation of ecosystem services (Adla et al., 2022). The loss of biodiversity is particularly pronounced in regions with high levels of species endemism, where urban expansion can lead to the extinction of unique species (Zubair et al., 2015).

The fragmentation of habitats caused by urban sprawl also poses significant challenges for the conservation of biodiversity, as it disrupts species movement, breeding, and feeding patterns (Gao & O'Neill, 2020).

The degradation of ecosystem services resulting from urban expansion has significant implications for human well-being (mohammed et al.2022). Ecosystem services, such as water purification, air quality regulation, and climate moderation, are essential for maintaining environmental sustainability and human health (UN-Habitat, 2014). The loss of these services can lead to increased vulnerability to environmental hazards, such as floods, heatwaves, and air pollution (Seto et al., 2012). Additionally, the degradation of ecosystem services can have economic consequences, as it undermines the ability of natural systems to support agriculture, forestry, and other (Zubair et al., 2015).

2.4.3. Climate Change Implications

Urban expansion also has significant implications for climate change (Li et al.2022). The conversion of natural landscapes into urban areas contributes to the increase in greenhouse gas emissions, particularly through deforestation, land use change, and the energy-intensive nature of urban development (Magazzino et al.2023). The loss of forests and other natural habitats reduces the ability of ecosystems to sequester carbon, exacerbating the impacts of climate change (Farid et al.2022). Additionally, urban areas are often associated with higher levels of energy consumption, transportation emissions, and waste generation, all of which contribute to global warming (Yang et al., 2020).

The impacts of climate change are also felt more acutely in urban areas, where the concentration of people, infrastructure, and economic activities increases vulnerability to climate-related hazards (Monteiro et al., 2022). Rising temperatures, increased frequency of extreme weather events, and sea-level rise all pose significant challenges for urban sustainability and resilience (McPhearson, 2020). The intersection of urban expansion and climate change requires coordinated efforts to mitigate emissions, adapt to changing conditions, and promote sustainable urban development (Cobbinah & Aboagye, 2017; Lee et al., 2020).

2.5. Geographical Information System (GIS) and Remote Sensing in LULC Monitoring of Urban Expansion's Impact on Forests

Geographic Information Systems (GIS) and remote sensing technologies play a critical role in monitoring land use and land cover (LULC) changes, particularly in assessing the impacts of urban expansion on forested areas (Faruque et al.2022; Monteiro et al., 2022; Anees et al., 2020). Remote sensing provides high-resolution imagery and temporal data that enable the detection of changes in land cover over time, offering valuable insights into the extent and rate of deforestation and urban sprawl (Woodcock et al.2020). By analyzing satellite imagery, researchers can identify and quantify areas of forest loss, monitor fragmentation, and evaluate the encroachment of urban areas into forested landscapes (Zhang et al., 2020). GIS complements remote sensing by allowing for the integration and analysis of spatial data, enabling the visualization of urban growth patterns and their impacts on forests (Anees et al., 2020). This combination of technologies supports effective forest management and urban planning by providing detailed spatial and temporal data on land cover changes (Zerouali et al.2023).

2.6. Ecosystem Services Valuation Using Costanza et al. (1997) and Kindu et al. (2016) Frameworks

Ecosystem services valuation is essential for understanding the economic impacts of urban expansion on forested areas (Puplampu & Boafo, 2021). Costanza et al.'s (1997) framework provides a comprehensive approach to valuing ecosystem services by quantifying the benefits derived from natural ecosystems, such as carbon sequestration, water regulation, and habitat provision. This valuation helps in assessing the trade-offs between urban development and ecosystem services, highlighting the economic importance of maintaining forest ecosystems (Cueva et al.2022). Kindu et al. (2016) further refine this approach by using an equivalent coefficient of ecosystem services valuation (ESV) to estimate the value of ecosystem services in different land use scenarios. By applying these frameworks, researchers can evaluate how urban expansion affects the delivery of ecosystem services and guide policy decisions towards more sustainable land use practices (Lumeng & Jianguo, 2022). Integrating these valuation methods with GIS and remote sensing data enhances the understanding of the ecological and economic

implications of land cover changes, providing a robust basis for conservation and urban planning strategies (Costanza et al., 1997; Kindu et al., 2016).

2.7. Policy and Planning Influences

Urban expansion is also heavily influenced by policy and planning decisions at the local, regional, and national levels. Land use policies, zoning regulations, and infrastructure investments all play a critical role in shaping the pace and pattern of urban growth (Goodfellow, 2013). In many cases, urban expansion is driven by government policies that promote the development of new residential, commercial, and industrial areas, often at the expense of agricultural land and natural ecosystems (West et al., 1999; Seto et al., 2012). Additionally, the lack of effective urban planning and governance can lead to uncontrolled urban sprawl, with significant social, economic, and environmental consequences (UN DESA, 2019).

The role of policy and planning in urban expansion is particularly evident in the development of infrastructure, such as roads, highways, and public transportation systems (Narayanaswami, 2017). These investments can facilitate the outward spread of urban areas, making it easier for people to live and work in suburban and exurban areas. However, the failure to coordinate infrastructure development with land use planning can lead to fragmented urban landscapes, increased traffic congestion, and environmental degradation (Morshed et al., 2017;OECD/SWAC, 2020).

2.8. Policy Responses and Sustainable Development

Effective policy responses are essential for addressing the challenges posed by urban expansion and forest loss (Simkin et al.2022). Governments and policymakers must adopt strategies that promote sustainable urban development, protect forests and natural ecosystems, and address the socioeconomic needs of marginalized communities (Spyra et al., 2021).This includes the implementation of land use policies, zoning regulations, and conservation measures that balance the needs of urban growth with the protection of natural resources (Kelly-Fair et al.2022).

Sustainable development requires the integration of social, economic, and environmental considerations into urban planning and governance (Cobbinah & Addaney, 2022). This includes promoting green infrastructure, reducing greenhouse gas emissions, and enhancing the resilience

of urban areas to climate change (Xu & Zhao, 2021). Additionally, policies that promote social equity, protect the rights of indigenous and rural communities, and ensure the fair distribution of resources are critical for achieving sustainable and inclusive urban development (Pineo, 2022). Addressing the challenges of urban expansion and forest loss requires a coordinated and multi-sectoral approach that recognizes the interconnectedness of social, economic, and environmental systems (Li et al.2023).

2.9. Existing Policies and Strategies regarding to Forestry in Rwanda

Although Rwanda's forestry policies are robust, issues like illegal logging and the low productivity of man-made forests remain significant challenges (Muheirwe, 2023). Addressing these problems is essential for sustainable forest management, especially in areas experiencing rapid urbanization such as Rubavu (Bizimana and Hategekimana, 2024). The Ministry of Environment (2019) emphasizes that Rwanda's development strategy prioritizes not only economic growth but also the effective management of environmental resources and climate change. In this framework, Rwanda has committed to the Sustainable Development Goals (SDGs), focusing on economic advancement, environmental sustainability, and social inclusion (Malonza & Ortega, 2022).

To ensure responsible forest management, Rwanda has integrated forest conservation into its national development agenda, including the National Strategy for Transformation (NST1) and Vision 2050. The Ministry of Environment (MoE) oversees the protection of the environment and the sustainable management of natural resources through various agencies, including the Rwanda Forestry Authority (RFA), which is responsible for implementing policies and enhancing forest quality and productivity (MoE, 2017).

The Constitution of Rwanda (amended in 2015) serves as the supreme legal framework for forest management, recognizing forests as vital natural assets and mandating the protection and promotion of the environment (Art. 22 and 53) (Adekola et al., 2021). Vision 2020 and NST1 prioritize a Green Economy approach, focusing on sustainable natural resource management to transition Rwanda towards a green economy (Dusingizimana et al.2022). Vision 2050 aims to elevate Rwanda to a high-income economy with improved living standards, supported by the Green Growth and Climate Resilience Strategy (GGCRS) and the Nationally Determined

Contributions (NDCs), which emphasize adaptation and mitigation strategies (NST1, 2017; NLUMP, 2020). Rwanda's National Forestry Policy (2010, revised in 2017), Forest Law (2013), and other key documents, such as the Forestry Sector Strategic Plan (2017-2021) and the ENR Strategic Plan (2018-2024), provide the essential legal and policy frameworks for the protection, sustainable use, and enhancement of forest resources. These policies and laws are complemented by initiatives like the Bonn Challenge, which aligns with Rwanda's commitment to forest conservation and sustainable land management.

Although Rwanda implements various policies and strategies, the Ministry of Environment has identified several challenges. High population growth leads to increased competition among forestry, land, and water resources, raising demand on these limited supplies (Li et al., 2021NST1, 2017; NLUMP, 2020). However, this population growth also presents an opportunity: with the population growth rate and 40% of the population below working age, Rwanda has the potential for a "demographic dividend," which could foster new and innovative thinking and action (MoE, 2017). The Ministry also highlighted issues in the forest sector, such as unproductive forest management practices due to illegal tree cutting, low productivity of man-made forests, uneven distribution of forests across the country, and the over-reliance on a single species (Eucalyptus), which collectively present significant challenges (Ministry of Environment, 2017).

2.10. Research Gaps in Urban Expansion and Forest Cover Degradation: A Critical Review and Future Directions in the Context of Rubavu City, Rwanda

Research into the effects of urban expansion on forest cover degradation in Rubavu City, Rwanda, highlights several significant gaps in the existing literature. Although numerous studies have explored urbanization's impact on forest cover at a broader scale (e.g., Bizimana & Hategekimana, 2016; Kabera & Tushabe, 2021), there is a distinct lack of research addressing the specific dynamics and drivers of forest degradation in Rubavu City. This absence of localized studies limits our understanding of how urban expansion uniquely affects forest ecosystems in this context (Munyaneza et al., 2020; Ndishimye et al., 2021).

Furthermore, the existing literature often fails to comprehensively analyse the complex interplay between urban expansion and forest cover degradation, especially in post-conflict regions like Rubavu City (Munyaneza et al., 2020; Niyonsenga et al., 2023).Understanding the specific

mechanisms through which urban expansion contributes to forest degradation in Rubavu is essential for developing targeted conservation strategies and urban planning frameworks (Queno; Nema et al., 2023; Bower et al., 2022). This research gap necessitates a focused investigation into how urbanization impacts forest dynamics in Rubavu City.

Urban planning research has increasingly emphasized the importance of climate resilience in mitigating the adverse effects of urban sprawl. However, most studies have concentrated on larger metropolitan areas, such as Kigali (Kamanzi et al., 2021; Gahima & Baryamureeba, 2022).This leaves a gap in understanding how Rubavu's urban planning strategies incorporate sustainable development and the preservation of green spaces amidst rapid urban expansion. The interaction between urban growth and resilience to climate-induced challenges, such as flooding and landslides, has received limited attention in Rubavu (Habarurema et al., 2022; Byiringiro et al., 2023).

Moreover, while much research in Rwanda has focused on deforestation in rural regions and conservation areas like Nyungwe and Volcanoes National Parks (Nyundo et al., 2019; Uwizeye et al., 2020), there is a notable lack of studies examining how urban expansion in smaller cities like Rubavu impacts surrounding forest ecosystems. Specifically, studies quantifying changes in forest carbon storage and declines in other ecosystem services due to urban expansion in Rubavu are sparse (Gakuba et al., 2022; Nshimiyimana et al., 2023). This gap underscores the need for a more targeted approach to evaluating local ecological degradation.

As the conservation value of intact forests becomes increasingly crucial, particularly within sustainable development frameworks such as payment for ecosystem services (PES), research on the effectiveness and challenges of PES schemes, including the UNFCCC's REDD+ mechanism, is essential (Alamgir et al., 2020; Svensson et al., 2020; Munyaneza et al., 2023). This research is vital for addressing forest degradation and reducing greenhouse gas emissions.

Future research should focus on the intricate interactions between urban expansion and forest cover degradation, providing valuable insights for informed policy-making and sustainable urban development. Proposed methodologies and approaches will play a critical role in advancing our understanding of these complex dynamics and guiding future research endeavors in Rubavu City.

Chapter Three: Research Methodology

This chapter presents in detail the methodology that was used by the researcher to carry out this research. It details the study area, research design, data types and sources, their collection as well as their analysis approaches and research validity.

This research employed a mixed-methods approach, combining GIS tools, remote sensing, and both qualitative and quantitative methods. GIS and remote sensing were used to conduct a spatial-temporal analysis of urban expansion and forest cover changes. Quantitative methods included statistical analysis of land use and land cover (LULC) data, while qualitative methods involved reviewing secondary data and conducting field observations for ground truthing and accuracy assessment. To better interpret these LULC results, the researcher used qualitative data collection from secondary data in form of literature review. Additionally, the study relied on the observation primary data collection for taking GPS point for field check and for accuracy assessment

3.1. Brief description of the Study area

This study was conducted in Rubavu City, a secondary urban center located in Rubavu District, one of the seven districts in the Western Province of Rwanda (Figure 2). The district covers an area of 388.3 km² and is strategically situated on the shores of Lake Kivu, bordering the Democratic Republic of Congo to the north and west, Nyabihu District to the east, and Rutsiro District to the south. Rubavu's location as a key business and tourism hub makes it an essential area for analyzing the impacts of urban expansion on forest cover.

Rubavu District features a varied topography and climate, influenced by its equatorial location. Average temperatures range from 15°C in the higher elevations, where nighttime temperatures can drop to as low as 6°C, to 20°C near Lake Kivu (Seshaba et al.2024). The district receives an annual rainfall of between 1200 mm and 1500 mm (Omonijo et al.2023). The soil composition varies significantly across the district: the northwest is characterized by rich but shallow soils composed of volcanic ash and decomposed lava, while the southeastern areas contain deeper, poorer soils, often acidic and sandy, prone to erosion.The district's environment is increasingly affected by climate change, with more frequent and severe floods and droughts. These events pose significant socioeconomic challenges, including landslides, soil erosion, crop losses, and damage to infrastructure. Deforestation, particularly in the Gishwati forests, has exacerbated the vulnerability of downstream areas to intensified rainfall (Bizimana and Hategekimana, 2024). Rubavu District

is located within the Kivu Nile and Sebeya catchment areas, and the inadequate management of stormwater often leads to flooding. When stormwater mixes with sewage, it can cause severe health risks and contamination of both land and water sources. Flood-prone areas in the district include Amahoro, Byahi, Cyanika, Gisenyi Airport, Stadium, Gisenyi Umuganda, Kabuye, Karunda Road, Nengo, UTB Gisenyi Campus, and Rukoko.

The demographic profile of Rubavu District further emphasizes its significance as a study area. According to the 5th Rwanda Population and Housing Census (PHC5) of 2022, the district's population has grown to 546,683, a substantial increase from the 403,662 recorded in the 2012 census. The district is predominantly urban, with 53.9% of its population living in urban areas and 46.1% in rural regions. The population is notably young, with 60.9% under 25 years old, reflecting a high recent fertility rate, while the elderly population (60 years and above) makes up 4.8% of the total.

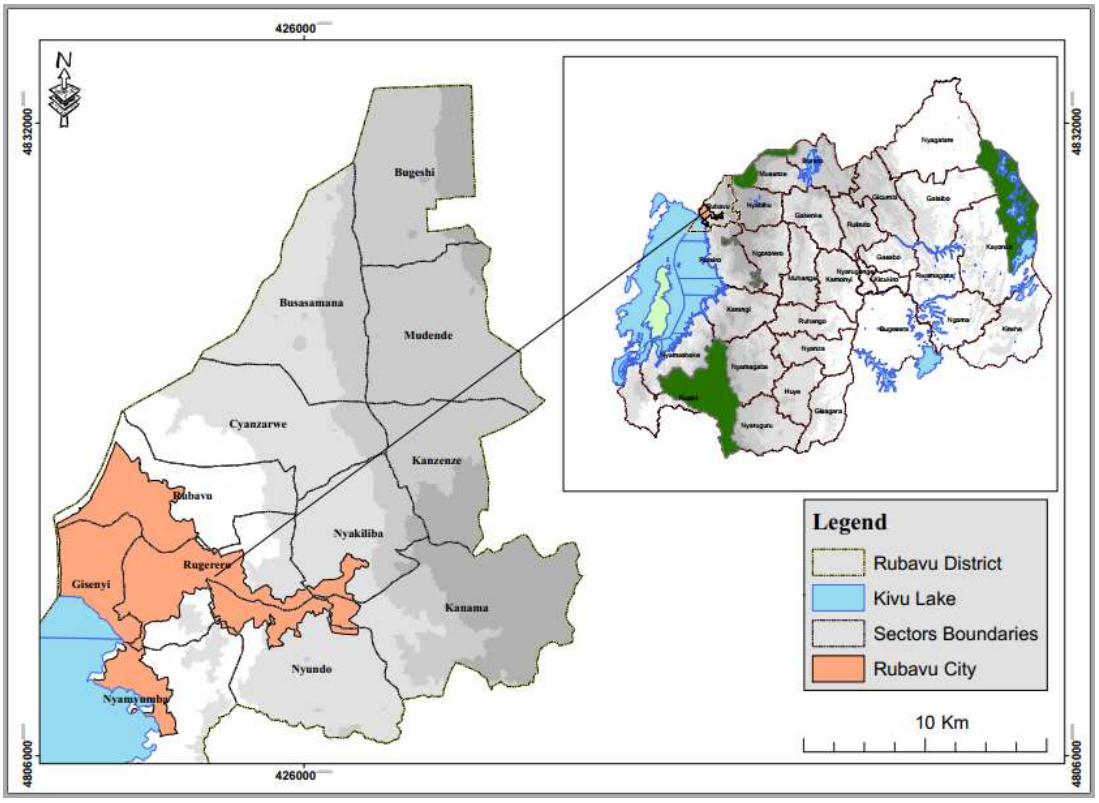

Figure 2: Location of Rubavu city as study area

Data Source: NISR, 2022

3.2. Secondary Data Sources

The secondary data sources for this research include existing literature, spatial datasets, and Landsat imagery from the United States Geological Survey (USGS). These resources were integral to conducting a spatio-temporal analysis of urban growth and forest cover changes. The literature review helped identify research gaps and informed the study's objectives, while spatial data from the USGS and Google Earth served as the foundation for Land Use/Land Cover (LULC) classification and analysis.

3.2.1 Existing Literature

An extensive review of existing literature guided the selection of this research topic, helping to identify the research gap this study aims to address. The literature review also played a crucial role in shaping the research objectives and problem statement. The sources consulted include books, scientific journal articles, and official reports from reputable organizations such as the Rwanda Environment Management Authority (REMA), National Institute of Statistics of Rwanda (NISR), Ministry of Environment, Rwanda Forestry Authority (RFA), and Global Forest Watch. These references were instrumental in framing the discussion and analysis of the research findings.

3.2.2 Spatial Data

The spatial data utilized in this research include satellite imagery and the administrative boundaries of Rubavu District and Rubavu Secondary City. The study relied on images from the Earth Resources Observation and Science (EROS) Data Center of the USGS, which are freely available and thus cost-effective. Landsat images from the years 2000, 2010, and 2020 were acquired from the USGS for land cover classification, while Google Earth images from the same years were employed for accuracy assessment and to define land cover classes by selecting and recognizing sample areas.

3.3. Primary Data

Primary data for this research were collected through interviews with key stakeholders and field observations. These sources provided qualitative insights that complemented the quantitative

analysis and offered a deeper understanding of local perceptions and challenges related to urban expansion and forest cover changes.

3.3.1 Interviews

Interviews were conducted with key stakeholders, including Rubavu District officials responsible for forestry, natural resources, and environmental management. The primary objective of these interviews was to gather qualitative data on the impacts of urban expansion on forest cover, existing mitigation measures, and suggestions for sustainable urban planning and forest conservation. Structured interviews were carried out using a pre-designed questionnaire to ensure consistency and comprehensiveness in the responses.

The questionnaire addressed topics such as the evolution and drivers of urban expansion in Rubavu City, observed changes in forest cover over the past two decades, the perceived impacts of urban expansion on local ecosystems, and the effectiveness of current mitigation measures. It also explored additional strategies for protecting and restoring forest areas, community involvement in forest conservation efforts, and recommendations for improving policies and regulations to balance development with conservation.

3.3.2 Field Observations

Field observations were conducted to validate and supplement the data obtained from satellite imagery and interviews. The primary aim of these on-site visits was to observe and document the current state of forest cover, urban expansion, and land use changes in key areas within Rubavu City. These observations provided ground-truth data that supported the spatio-temporal analysis and helped identify areas where urban expansion has significantly impacted forest cover. Additionally, field observations allowed for interactions with local communities, offering anecdotal evidence on the environmental changes and challenges they are facing.

3.4. Analytical Framework

The analytical framework involves several steps: (1) collecting and preprocessing satellite imagery, (2) conducting LULC classification using supervised classification techniques, (3) performing accuracy assessments, and (4) analysing the spatial-temporal changes in forest cover

and urban expansion. The framework also includes identifying conservation strategies and sustainable forest management practices based on the findings. The analytical framework of this research is shown on the following figure:

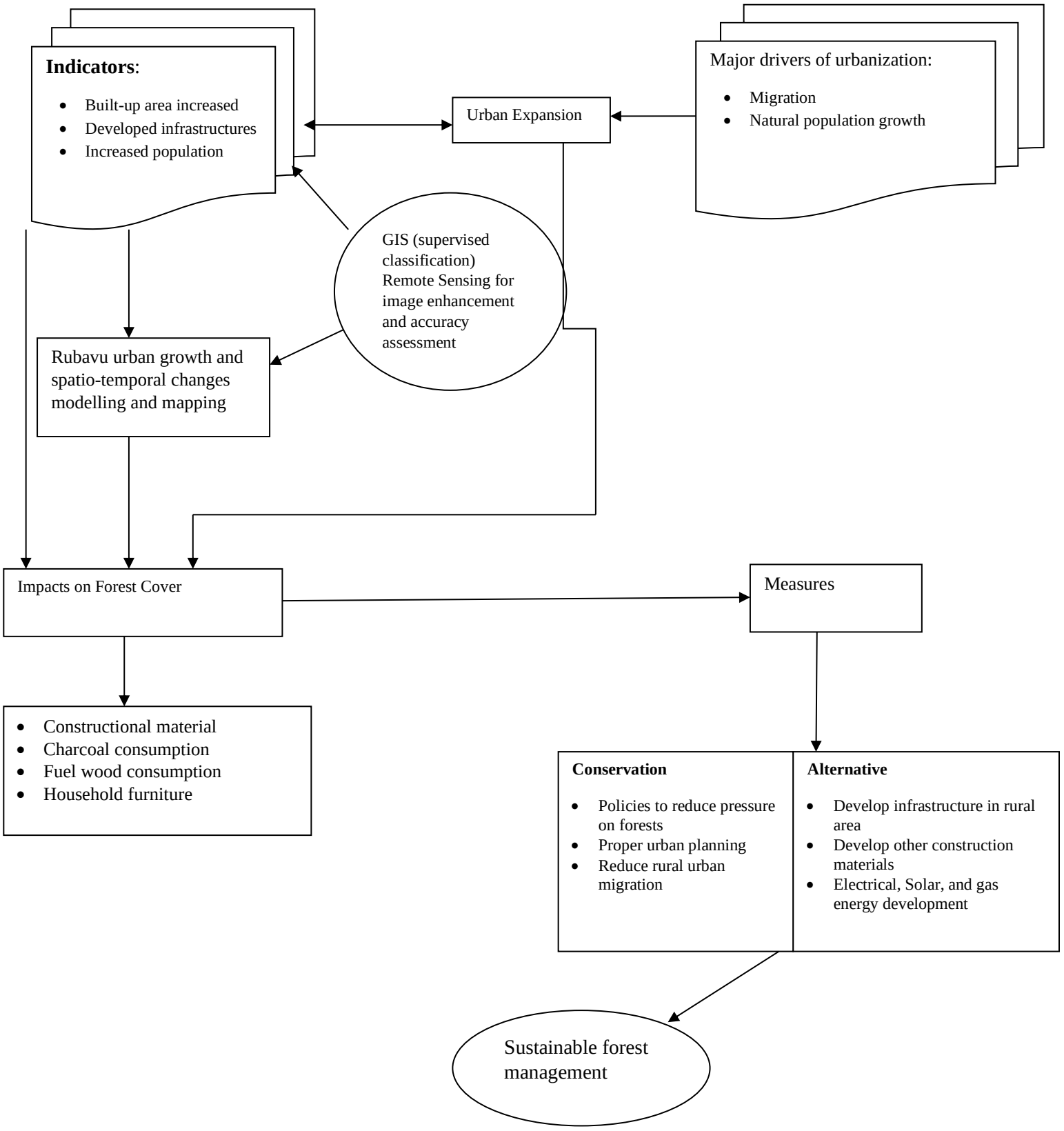

Figure 3: Analytical framework

3.5. Data Analysis and Interpretation

3.4.1. Land Use Land Cover Classification

Image classification techniques were employed to produce the Land Use and Land Cover (LULC) maps. The LULC patterns were generated for three years: 2000, 2010, and 2020. Landsat 5 TM was used for the year 2000, Landsat 7 ETM+ for 2000, and Landsat 8 (OLI_TIRS) for 2020. These images, corresponding to row/path 60/161 and having a ground resolution of 30 meters, were used to create the land use and land cover maps.

Landsat images were visually enhanced to optimize their quality through colour correction and band combination using ERDAS Imagine 2014. Subsequently, these enhanced images were exported to ArcMap, where a Supervised Classification technique through maximum likelihood method was applied in GIS. For each Land Use and Land Cover (LULC) class, reference training points were taken to create training signatures. The Signature Editor tool of Spatial Analyst menu of ArcMap 10.8 was utilized to delineate signature polygons. Features which look similar characteristics of LULC types were drawn on image. Several training sample areas for each LULC types with different characteristics were created before merging these different areas into single signature class. Supervised classification was performed using maximum likelihood technique. During the LULC classification process, various LULC types were identified. These LULC categories are: 1) Built-up, 2) Bare land, 3) Agricultural land, and 4) Forest. Definition for each category is provided in the table below.

Table 1: Land use Land cover class's definitions

No	Classes	Definition
1	Built up	The area containing buildings, paved roads and other built/manmade infrastructures
2	Bare land	Area consisting bare land with no vegetation cover and unpaved road
3	Forest	Area of forest, shrubs and bushes
4	Agricultural land	Area consisting cultivated area

Ground truth accuracy, User Accuracy, Overall accuracy and Kappa coefficient of Image Classification

The Overall accuracy, Kappa coefficient, User accuracy and Ground truth accuracy were calculated using the following formulas:

$$\textbf{Overall accuracy} = \frac{\text{total number of correctly classified pixel(Diagonals)}}{\text{total number of Reference pixels}} \times 100$$

$$\textbf{Kappa coffiecient} = \frac{\text{Ts} \times \text{TCs} - \sum(\text{Column total} \times \text{Row total})}{\text{Ts}^2 - \sum(\text{column total} - \text{Row total})}$$

$$\textbf{User accuracy} = \frac{\text{Number of correctly classified pixels in each category}}{\text{Total number of reference pixels in that category(the Row total)}} \times 100$$

$$\textbf{Ground truth accuracy} = \frac{\text{Number of corrected classified pixels in each category}}{\text{Total number of reference pixels in that category(the column total)}} \times 100$$

Where:

T(s): is total sample and T(cs): is total corrected sample

Landsat images from 2000, 2010, and 2020 were classified using supervised classification techniques. The following are the obtained ground truth accuracy and user accuracy.

Table 2: Ground truth accuracy and User accuracy (in %)

	Ground truth accuracy				User accuracy			
Year	Built up	Bare land	Agricultural land	Forest	Built up	Bare land	Agricultural land	Forest
2000	100	100	91.6	100	90.9	100	100	100
2010	100	100	86.6	80	80	82	78.8	100
2020	93.3	90.9	95.83	100	87.5	100	95.8	100

Source of data: USGS, 2024 (https://earthexplorer.usgs.gov/)

Ground truth accuracy measures how well the classified images represent real-world conditions, while user accuracy evaluates the reliability of the classifications for practical use. High accuracy metrics indicate that the LULC maps produced are reliable for analysing urban expansion and forest cover changes. User accuracy, on the other hand, evaluates the reliability of the classified image. It assesses how well the map's representations correspond to the actual conditions on the ground. Essentially, user accuracy determines the probability that a given point on the map indeed reflects the real-world scenario it is supposed to depict. High user accuracy signifies that the map is a dependable tool for real-world applications and decision-making

Table 3: Kappa Coefficient and Overall Accuracy of Image Classification

Years	Kappa coefficient	Overall accuracy
2000	0.9552	98.27
2010	0.8424	88
2020	0.9355	95.23

Source of data: USGS, 2024 (https://earthexplorer.usgs.gov/)

Landsat images from 2000, 2010, and 2020 were classified using supervised classification techniques. The overall accuracy and Kappa coefficient were calculated to assess the reliability of the classifications. Results showed high overall accuracy, indicating reliable LULC maps. For example, the overall accuracy for 2020 was 95.23%, with a Kappa coefficient of 0.9355, suggesting a high level of agreement between the classified images and ground truth data.

The Land Use Land Cover (LULC) classification using Landsat images from 2000, 2010, and 2020 faced several limitations, including sensor and temporal variability, the quality of training data, and ground truth data constraints. Different Landsat sensors introduced potential inconsistencies in image quality, which were mitigated through consistent preprocessing techniques. The accuracy of the classification relied heavily on representative training samples, and despite high accuracy metrics (overall accuracy and Kappa coefficient), there remains some uncertainty due to potential limitations in ground truth data. Seasonal and phenological effects could also influence classification results, but efforts were made to standardize the timing of image acquisition. The 30-meter spatial resolution of Landsat imagery led to mixed pixels in heterogeneous areas, addressed by using the Supervised Classification method to distinguish between classes as

effectively as possible. Overall, while the methods employed achieved high accuracy, acknowledging these limitations is crucial for understanding the reliability and applicability of the LULC maps for analyzing urban expansion and forest cover changes.

3.4.2. Detection of spatio-temporal changes in forest cover correlate with urban expansion and other land use changes in Rubavu City

This section involves analyzing the spatio-temporal changes in forest cover and correlating them with urban expansion and other land use changes in Rubavu City. The analysis will include quantifying the extent of forest cover change over time and correlating it with urban expansion data. Spatio-temporal analysis will assess the spatial distribution and temporal dynamics of forest cover loss and urban growth. Additionally, Ecosystem Service Valuation (ESV) will be used as an indicator of change, evaluating the economic value of ecosystem services provided by forested areas. This will highlight the economic and ecological impacts of urban expansion.

Table 4:Valuation coefficients (USD per hectare per year) for the modified ecosystem services (Kindu et al., 2016)

System Services (ES)	**Forest Land (USD ha^{-1} yr^{-1})**
Water supply	8
Food production	32
Raw material	51.24
Genetic resources	41
Water regulation	6
Water treatment	136
Erosion control	245
Climate regulation	223
Biological control	0
Gas regulation	13.68
Disturbance regulation	5
Nutrient cycling	184.4
Pollination	7.27

Soil formation	10
Habitat/refugia	17.3
Recreation	4.8
Cultural	2
Total ES value	**986.69**

Source: Adapted from Negussie et al. (2019)

The methodology for evaluating ecosystem services (ES) values is based on the application of modified annual value coefficients for specific land cover/land use (LCLU) classes, as derived from Kindu et al. (2016). Table 4 outlines the valuation coefficients (USD per hectare per year) assigned to the ecosystem services provided by urban forests. The Equivalent Service Values (ESVs) for the urban forest category, as well as the total ESVs across the study period (2000, 2010, and 2020), were calculated using the following equation adapted from Negussie et al. (2019):

$$\boldsymbol{ESVft = (Akf * VCf)} \quad \boldsymbol{(1)}$$

Where *Akf* represents the forest area (in hectares) for the given period, and *VCf* is the value coefficient (USD per hectare per year) associated with the forest category for each ecosystem service function.

3.4.3. Evaluation of Urban Expansion Impacts

This section focuses on evaluating the extent to which urban expansion has affected forest cover within Rubavu City. The evaluation process will include an impact assessment to determine the direct and indirect impacts of urban expansion on forest cover. Environmental degradation will be analysed, including loss of biodiversity, increased soil erosion, and changes in microclimates. Stakeholder interviews will provide qualitative data to support the observed changes and offer insights into local perceptions and challenges related to urban expansion. Data from satellite imagery, ecosystem service valuation, and stakeholder interviews will be triangulated to ensure a comprehensive understanding of the impacts. By incorporating multiple data sources and perspectives, this section aims to provide a holistic view of the impacts of urban expansion on forest cover in Rubavu City.

3.4.4. Proposal of Mitigation Measures

The proposed strategies are derived from the analysis of urban expansion's impact on forest cover reduction, as well as insights gathered from stakeholder interviews detailed in the appendix 2. Additionally, policy recommendations for local authorities are provided to support the implementation of sustainable urban development and forest conservation measures. A comprehensive review of literature on global best practices for mitigating the effects of urban development on forests was also conducted to inform these proposals. The proposed mitigation strategies are designed to be both economically and socially viable, ensuring their feasibility and effectiveness in addressing the environmental challenges facing Rubavu City.

3.6. Limitations of Data and Methods

Variability in satellite sensor performance and temporal differences between images can affect data consistency. To address this, preprocessing techniques were standardized across Landsat images from different years, including radiometric and atmospheric corrections. Limited availability of comprehensive ground truth data could introduce uncertainties; however, field observations and stakeholder interviews were used to supplement and verify the data. Additionally, the 30-meter spatial resolution of Landsat imagery may lead to mixed pixels, but supervised classification methods with representative training samples were employed to mitigate this issue.

The accuracy of supervised classification depends on the quality of training data and the chosen algorithm. To improve accuracy, multiple training samples were collected, and the maximum likelihood method was used for its robustness. Accuracy assessment was expanded beyond overall accuracy and Kappa coefficient to include user accuracy and ground truth accuracy, providing a more comprehensive evaluation. Ecosystem service valuation also faced limitations due to the potential for local variations in valuation coefficients. Sensitivity analyses were conducted to explore these variations and their impact on overall valuation.

The study's temporal scope was restricted to specific years (2000, 2010, 2020), potentially missing long-term trends or recent changes. Despite this, a thorough spatio-temporal analysis was performed, and future research could incorporate more recent data. Additionally, the study’s findings were influenced by a limited number of stakeholder perspectives.

To address this, a diverse group of stakeholders was consulted, and field observations provided supplementary insights to capture a broader range of views.

Chapter Four: Results and Discussion

This chapter presents the outcomes of the Land Use and Land Cover (LULC) classification using Landsat images, providing a comprehensive analysis of LULC changes over time. It examines the expansion of urban and built-up areas through GIS-based LULC analysis, highlights the patterns of urban growth in Rubavu City, and investigates the forest loss attributed to this urban expansion. The findings offer insights into the dynamic interplay between urbanization and forest change in Rubavu City.

4.1.Analysis of Urbanization Trends and Expansion Patterns in Rubavu City (2000, 2010 and 2020)

The analysis of land use/land cover (LULC) data for Rubavu City from 2000 to 2020 reveals significant shifts in land use patterns, primarily driven by rapid urbanization. The data in Figure 4 and appendix 3 indicate a marked increase in the built-up area, which expanded from 5.09 km² in 2000, representing 10.47% of the total area, to 23.22 km² in 2020, accounting for 47.77%. This nearly fivefold increase underscores the city's rapid urban expansion, likely fueled by population growth, economic activities, and infrastructure development. As the city expanded, forest cover declined dramatically, decreasing from 20.17 km² in 2000 (41.50%) to 9.66 km² in 2020 (19.88%). This reduction in forested areas highlights the environmental cost of urban growth, as land previously occupied by forests was converted to residential and commercial uses.

Agricultural land also experienced a decline during this period, although the change was less pronounced compared to the decrease in forest cover. Agricultural areas decreased from 16.10 km² in 2000, representing 33.12% of the total area, to 13.26 km² in 2020 (27.28%). This shift suggests a transition in land use from agriculture to urban development, reflecting the changing economic priorities in Rubavu City, as highlighted in interviews conducted. The fluctuation in bare land is particularly noteworthy; while bare land initially increased from 7.25 km² in 2000 (14.91%) to 11.66 km² in 2010 (23.99%), it then dramatically decreased to 2.46 km² in 2020 (5.06%). This pattern could be attributed to phases of land clearing for development, followed by subsequent construction and vegetation growth as the urban infrastructure expanded, as explained during the interviews.

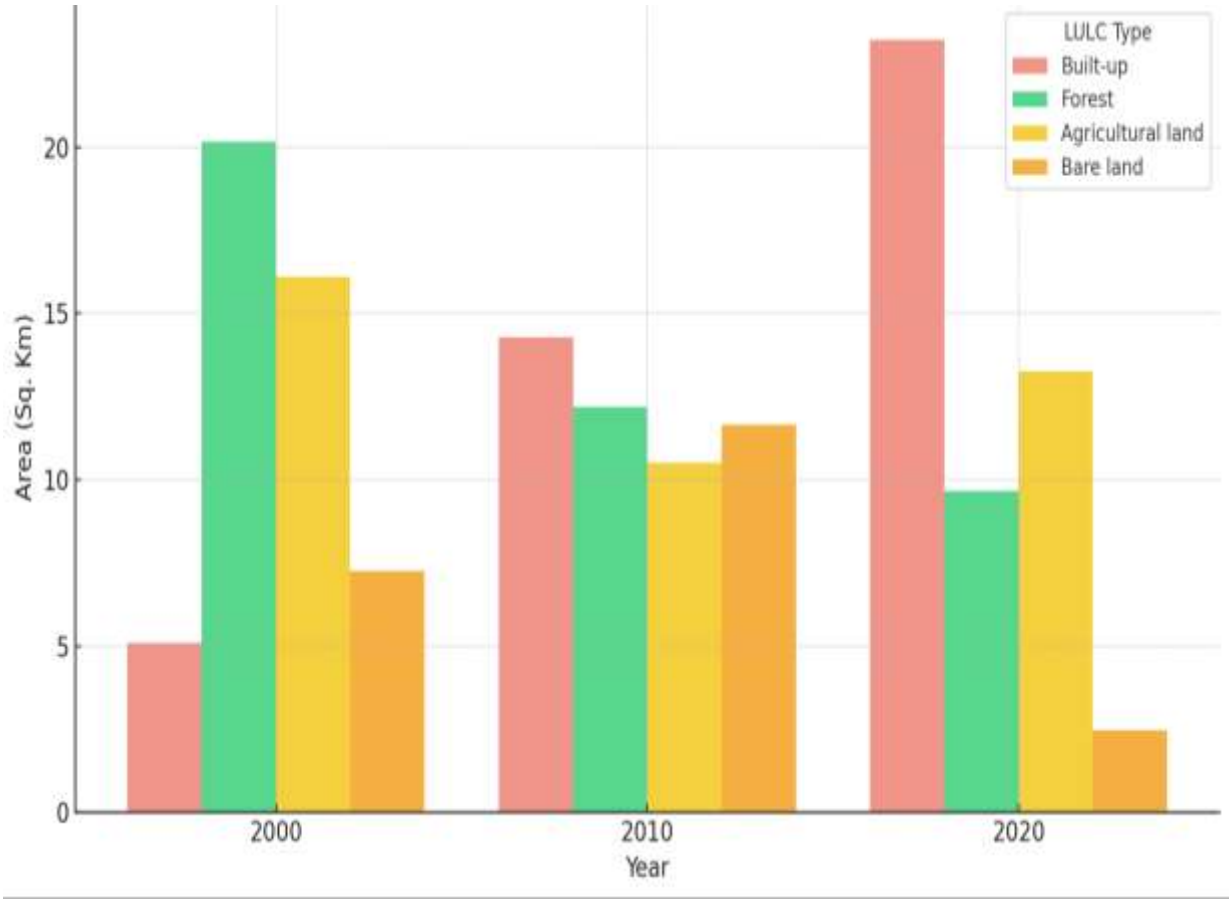

Figure 4:Land Use/ Land cover Change in Rubavu City (2000-2020)

The spatial distribution of urban expansion in Rubavu City, as shown in the map in Figure 5, reveals a concentric growth pattern radiating from the central business district, with significant development occurring along major transportation routes and in areas adjacent to Lake Kivu. This pattern indicates that the city's expansion has been strategically directed toward economically vital areas, reinforcing Rubavu's role as a business and tourism hub, as highlighted by District officials interviewed. However, the reduction in forest cover, particularly in peripheral areas, underscores the environmental challenges posed by such rapid urbanization. The encroachment of natural ecosystems to accommodate urban growth has significant implications for biodiversity, climate regulation, and ecosystem services, as highlighted by the District Environmental Officer.

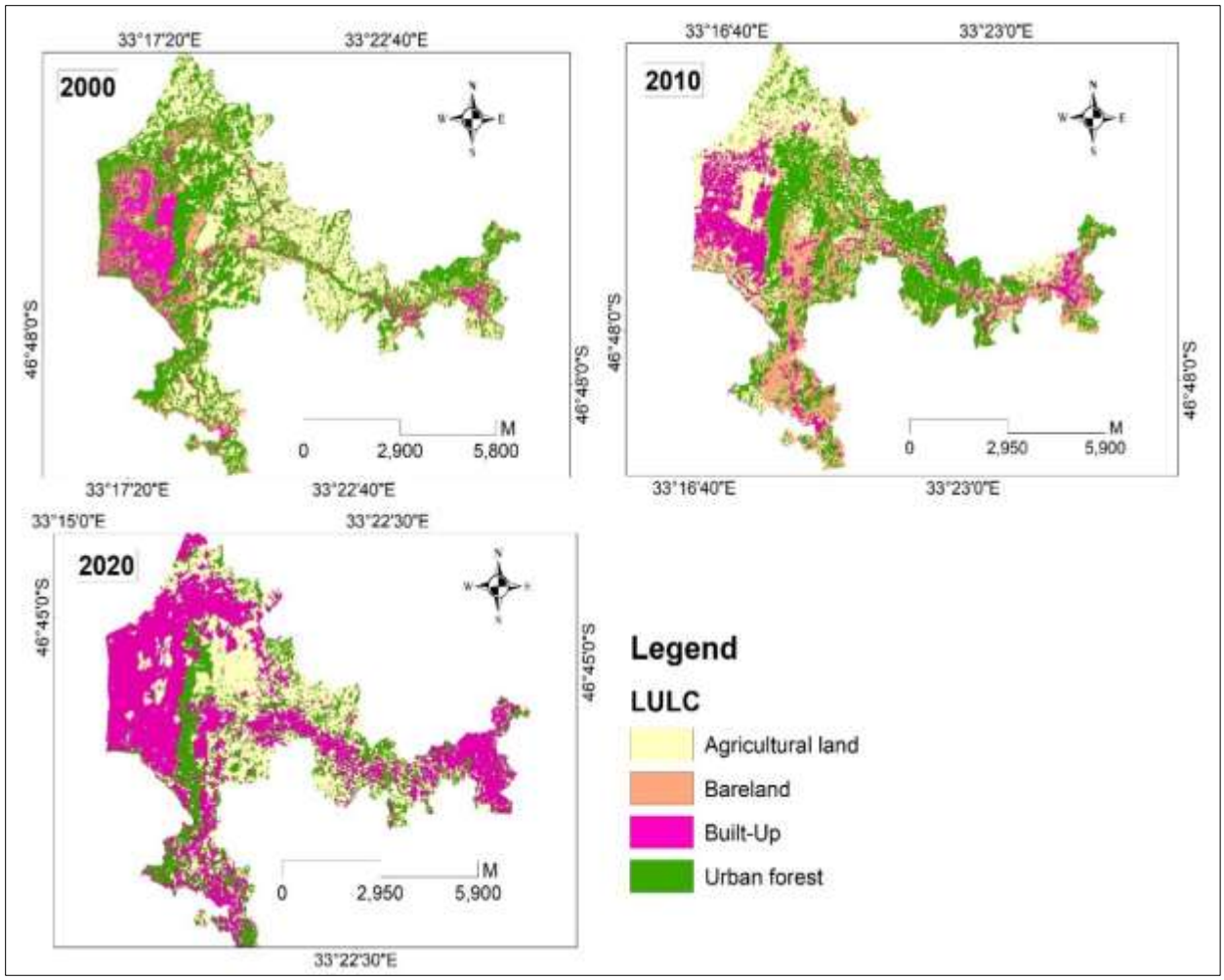

Figure 5:Land Use Land Cover, 2000,2010 and 2020.

The decline in forest and agricultural land in favor of urban expansion in figure 6, suggests a potential risk to the sustainability of local ecosystems and the services they provide. This trend underscores the need for a more balanced approach to urban planning that takes into account the long-term environmental impacts of land use changes, as will be further discussed in the following sections.

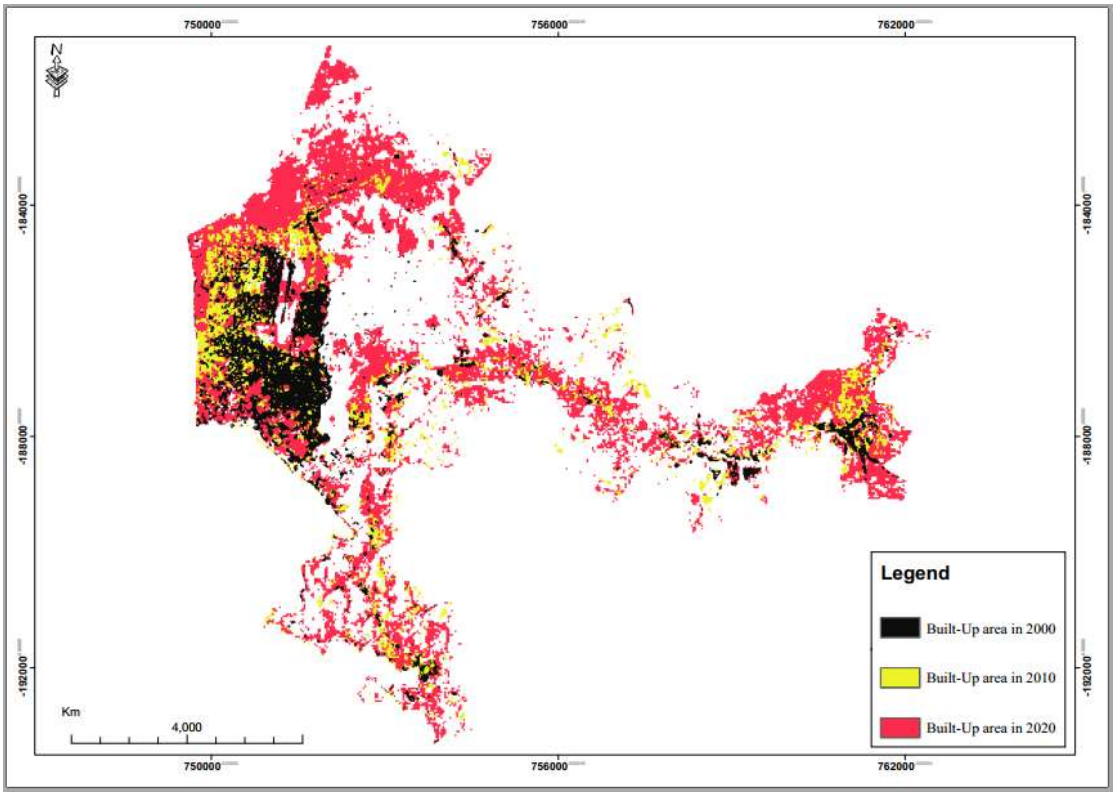

Figure 6: Distribution of built-up area for 2000 to 2020

4.2.Spatio-Temporal Analysis of Forest Cover Changes in Rubavu City (2000-2020)

The analysis of land cover changes in Rubavu City from 2000 to 2020 in Figure 7 and appendix 4, reveals a substantial decline in forested areas, highlighting the significant impact of urban expansion on the local environment. In 2000, forested areas constituted 41.51% of the total land area, but by 2010, this had decreased to 25.07%, and further to 19.88% by 2020. This drastic reduction underscores the rapid deforestation occurring over the two decades, driven largely by urbanization and related land-use changes.

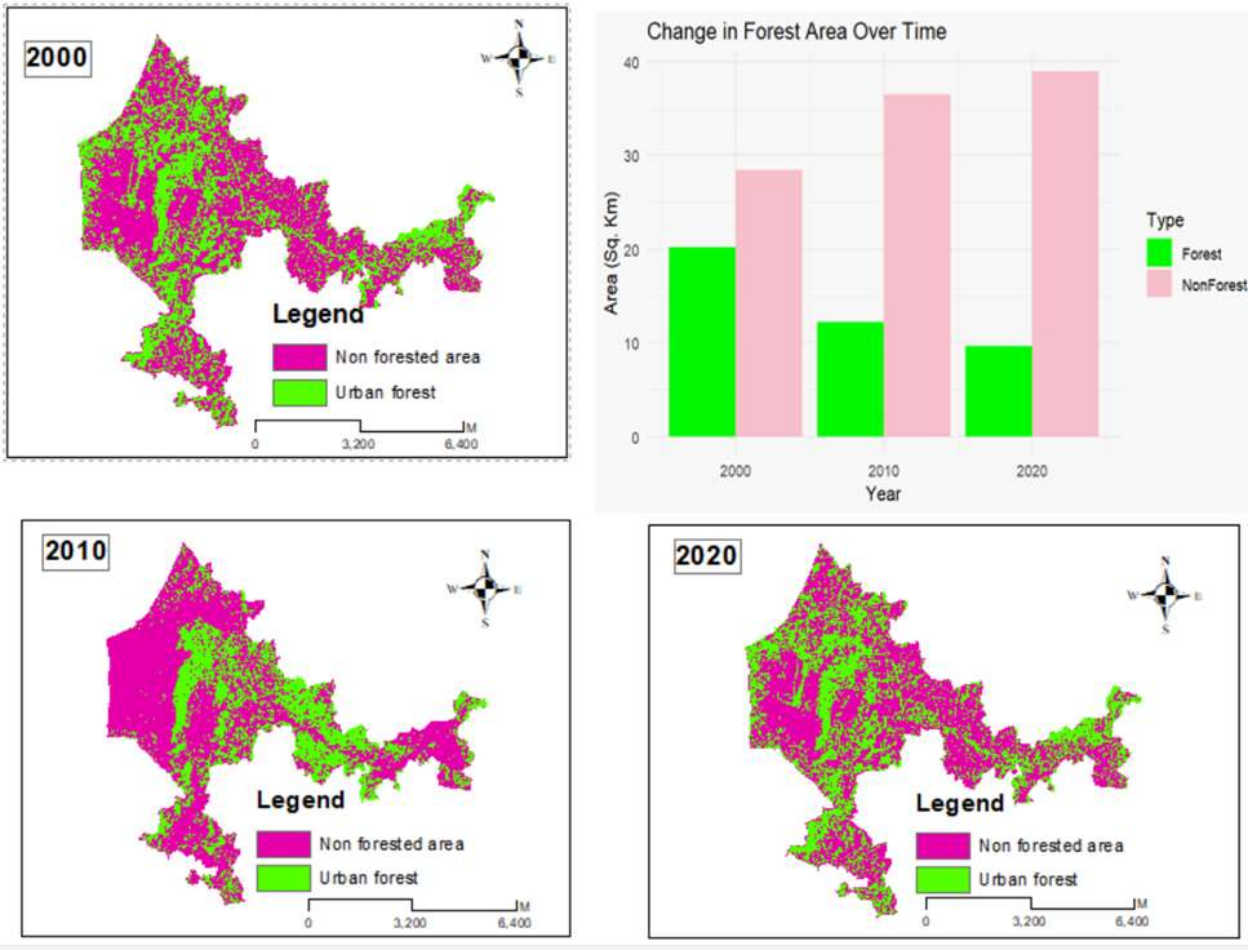

Figure 7: Change in forest area 2000,2010 & 2020

Conversely, non-forested areas have expanded consistently, covering 58.49% of the total area in 2000, increasing to 74.93% by 2010, and reaching 80.12% by 2020. This growth indicates a shift towards more intensive land uses, likely associated with the demands of a growing urban population and infrastructure development. The forest loss between 2010 and 2020 in Rubavu City in figure 8, is a clear reflection of the accelerating pace of urban growth during this period. The data shows that forested areas declined from 25.07% in 2010 to just 19.88% in 2020, a significant reduction within a decade. This decrease indicates that nearly one-fifth of the forest cover was lost as urban areas expanded, likely due to increased demand for land for residential, commercial, and infrastructural development. The loss of forested areas during this period underscores the environmental trade-offs of urbanization, as natural habitats are cleared to make way for urban infrastructure. This trend not only reduces biodiversity but also diminishes the ecosystem services provided by forests, such as carbon sequestration, water regulation, and soil stabilization.

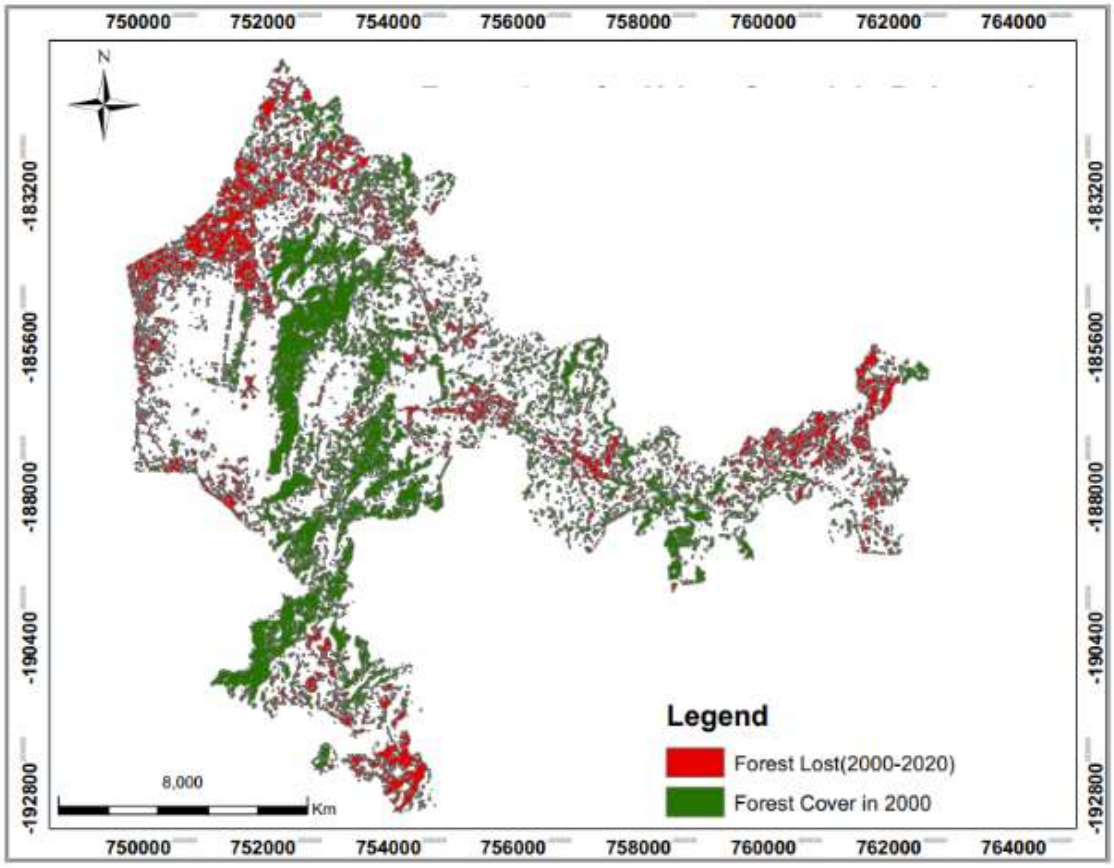

Figure 8:Forest loss between 2010 and 2020 due to urban growth

These findings emphasize the need for sustainable urban planning and effective forest conservation strategies in Rubavu City. The ongoing loss of forest cover not only threatens the availability of essential ecosystem services but also highlights the broader environmental consequences of unchecked urban expansion. Addressing these challenges will require concerted efforts, including reforestation initiatives, the creation of urban green spaces, and the integration of sustainable land use practices into urban planning to ensure long-term environmental sustainability.

4.3.Assessing the Impacts of Urban Expansion on Forest Ecosystem Services in Rubavu City: Proposing Evidence-Based Mitigation Strategies

4.3.1. The Impacts of Urban Expansion on Forest Ecosystem Services

The decline in forest cover corresponds with a marked reduction in the value of ecosystem services provided by these forests, as shown in figure 7 and appendix 5. The total value of ecosystem services dropped from USD 19,901.54 per hectare in 2000 to USD 12,017.88 per hectare in 2010,

and further to USD 9,531.43 per hectare by 2020. This reduction is particularly evident in key services such as erosion control, which decreased from USD 4,941.65 per hectare in 2000 to USD 2,366.70 per hectare in 2020, and climate regulation, which fell from USD 4,497.91 per hectare in 2000 to USD 2,154.18 per hectare in 2020.

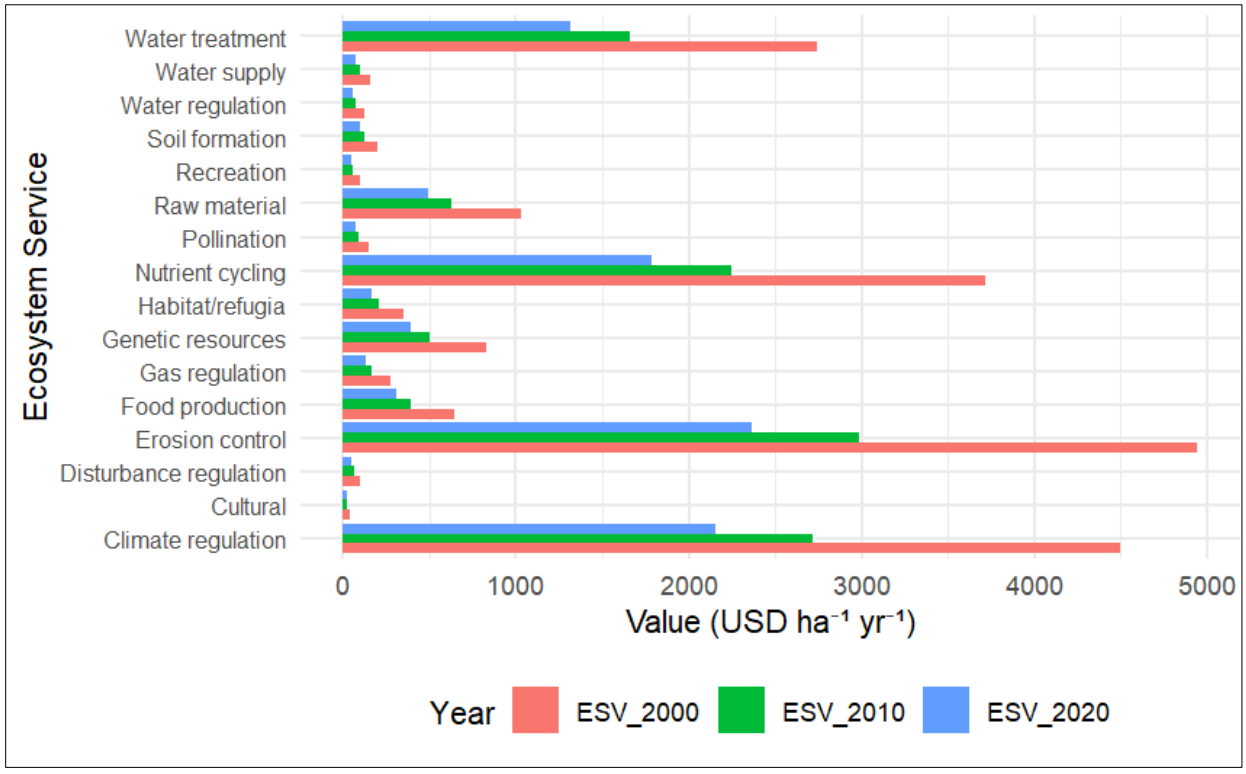

Figure 9:Effects of forest changes on the annual ecosystem service in the Rubavu City

The diminishing value of ecosystem services underscores the broader consequences of deforestation. Essential services like erosion control, flood mitigation, and climate regulation have experienced significant declines, impacting both environmental sustainability and the economic benefits derived from these services. Byiringiro et al. (2023) offer critical insights into the escalating susceptibility to landslides in Rubavu District, a situation further aggravated by deforestation and urbanization, which contribute to the deterioration of vital ecosystem services. An interview with a District official highlighted these issues, noting, ***"The impact on the urban microclimate is felt because Rubavu City is now hotter compared to the past. Landslide and flood hazards have increased in recent decades due to increasing buildup and deforestation."***

This firsthand account supports the quantitative findings and emphasizes the growing challenges posed by reduced forest cover.

4.3.2. Comparative Analysis of Urbanization Trends and Forest Ecosystem Impacts in Rubavu City

The urbanization trends observed in Rubavu City from 2000 to 2020, marked by a significant increase in built-up areas and a dramatic decline in forest cover, reflect broader patterns seen in other rapidly urbanizing cities worldwide. For example, Addis Ababa, Ethiopia, has experienced a similar trajectory of urban sprawl, where extensive development has led to substantial loss of green spaces and forested areas (Gizachew et al., 2021). In Addis Ababa, urban expansion has resulted in significant deforestation and a shift in land use from agriculture to built-up areas, mirroring the trends observed in Rubavu. Likewise, Nairobi, Kenya, showcases a comparable scenario where rapid urban growth has encroached upon critical ecosystems, leading to reductions in forest cover and alterations in land use (Munyati et al., 2019). Nairobi's expansion has resulted in significant environmental impacts, including decreased biodiversity and diminished ecosystem services, akin to those seen in Rubavu City.

Similarly, the urbanization patterns in cities such as Dakar, Senegal, and Manila, Philippines, reveal concentric growth around central business districts and along major transportation corridors, similar to the spatial distribution of urban expansion in Rubavu (Faye et al., 2022; Dela Cruz et al., 2018). This growth often leads to the conversion of natural landscapes into built environments, contributing to environmental degradation and reduced ecosystem services. The decline in forest ecosystem services in Rubavu—such as erosion control and climate regulation—parallels trends observed in other urbanized regions. For instance, deforestation in the Amazon Basin due to urban expansion has led to significant reductions in ecosystem services, affecting local and global climate regulation (Pereira et al., 2019). The reduction in the value of ecosystem services in Rubavu, from USD 19,901.54 per hectare in 2000 to USD 9,531.43 per hectare in 2020, highlights a similar trend seen in other cities facing rapid urbanization, where the environmental costs of development overshadow the benefits (Fischer et al., 2020).

These comparative insights underscore the global challenge of balancing urban development with the preservation of natural ecosystems. The experiences of cities like Addis Ababa, Nairobi, Dakar,

and Manila provide valuable context for understanding the impacts of urban expansion on forest ecosystems and the critical need for sustainable urban planning to mitigate these effects (Gizachew et al., 2021; Munyati et al., 2019; Faye et al., 2022; Dela Cruz et al., 2018).

4.3.3. Implications of Forest Cover Loss for Local Communities, Biodiversity, and Ecosystem Services

The extensive decline in forest cover in Rubavu City from 2000 to 2020 has significant repercussions for local communities. Forests provide crucial resources such as firewood, construction materials, and non-timber products. As forested areas diminish, communities face challenges in accessing these essential resources, leading to increased costs and reliance on less sustainable alternatives (FAO, 2020). Additionally, forest loss impacts local economies, especially those dependent on eco-tourism and forest-related industries. This potential loss of income and economic opportunities mirrors trends observed in other rapidly urbanizing regions (Gizachew et al., 2021).

Biodiversity is severely affected by the reduction in forest cover. Forests serve as crucial habitats for a diverse array of species, and their loss leads to habitat destruction, species displacement, and declines in wildlife populations, with some species potentially facing extinction (Pereira et al., 2019). Fragmented habitats also limit genetic diversity, increasing species vulnerability to diseases and environmental changes (Munyati et al., 2019). This disruption to biodiversity has broader ecological implications, affecting ecosystem stability and resilience.

The loss of forest cover also impacts vital ecosystem services. Forests play a key role in erosion control, soil health, and climate regulation (Fischer et al., 2020). Their decline results in increased soil erosion, reduced agricultural productivity, and higher atmospheric CO2 levels, contributing to global warming. Additionally, forests regulate water flow and quality by filtering pollutants and reducing runoff, and their loss can lead to deteriorated water quality and disrupted water cycles (Dela Cruz et al., 2018).

Addressing these challenges requires integrated efforts in urban planning and conservation. Sustainable land use practices, reforestation initiatives, and community involvement are crucial for mitigating the adverse effects of deforestation (Faye et al., 2022). By prioritizing these

strategies, Rubavu City can work towards balancing urban development with the preservation of natural resources, ensuring long-term environmental and economic sustainability (Gizachew et al., 2021; Kindu et al., 2016).

4.4.Strategies to achieve the sustainable forest in Rubavu City

The proposed strategies for achieving sustainable forest management in Rubavu City have been carefully developed based on a comprehensive approach that includes interviews with district officials and local community members, field visits, and an extensive review of existing literature. The strategies are designed to address the challenges posed by rapid urbanization, which has significantly impacted the city's forest cover, and to propose actionable solutions that align with both local needs and national and international environmental policies.

By integrating insights from key stakeholders and evidence from real-world observations, these strategies aim to balance urban development with forest conservation, ensuring that Rubavu City can continue to grow while preserving its natural resources. The following points outline specific approaches that are essential for fostering sustainable forest management in the face of ongoing urban expansion.

4.4.1. Integrating Forest Conservation into Urban Planning

To ensure sustainable forest management in Rubavu City, it is crucial to integrate forest conservation into urban planning frameworks. The current trend of urban expansion, as evidenced by the dramatic reduction in forest cover from 41.50% in 2000 to 19.88% in 2020, highlights the need for urban planning that prioritizes environmental sustainability. This can be achieved through the enforcement of existing environmental regulations and policies, such as Rwanda's National Land Policy (2019) and the Environment Law (2018), which mandate the consideration of ecological factors in land-use planning. By incorporating green spaces and forest corridors into urban designs, Rubavu City can balance the demands of urban development with the need to preserve critical forested areas.

Additionally, adopting international best practices in sustainable urban development, such as the principles outlined in the UN-Habitat's "New Urban Agenda" (2017), can further guide Rubavu

City's planning strategies. This agenda emphasizes the integration of environmental considerations in urban planning, promoting the creation of resilient and inclusive cities. Implementing such strategies will not only protect existing forests but also enhance the overall quality of life for urban residents by providing ecosystem services such as air purification, climate regulation, and recreational spaces.

4.4.2. Reforestation and Afforestation Initiatives

Reforestation and afforestation initiatives are essential strategies for restoring degraded forest areas in Rubavu City and mitigating the environmental impacts of urban expansion. The significant decline in forest cover necessitates a proactive approach to reforesting areas that have been converted to other land uses. Reforestation programs, guided by Rwanda's National Forest Policy (2018) and supported by community participation, can play a critical role in reversing deforestation trends. The policy outlines specific goals for increasing forest cover and promotes the use of indigenous species to restore ecological balance and enhance biodiversity.

Afforestation, or the establishment of forests on lands that have not previously been forested, can also contribute to increasing forest cover in urban and peri-urban areas. Programs like Rwanda’s Green Growth and Climate Resilience Strategy (2011), which emphasizes the importance of increasing forest cover to achieve environmental sustainability, provide a framework for such initiatives. By implementing large-scale afforestation projects, Rubavu City can not only restore lost forest areas but also create new green spaces that contribute to the overall ecological health of the region.

4.4.3. Promoting Agroforestry Practices

Agroforestry, the practice of integrating trees into agricultural landscapes, offers a sustainable solution to balancing urban expansion with forest conservation. As agricultural land in Rubavu City is increasingly being converted to urban use, agroforestry can serve as a compromise that supports both food production and forest conservation. This practice is aligned with Rwanda's Strategic Plan for Agriculture Transformation (PSTA 4), which advocates for sustainable land management practices that enhance productivity while conserving natural resources. By

encouraging farmers to adopt agroforestry, Rubavu City can maintain agricultural productivity while simultaneously increasing tree cover, thus mitigating the loss of forested areas.

Moreover, agroforestry contributes to ecosystem services such as erosion control, water regulation, and carbon sequestration, which are critical in the context of rapid urbanization. The practice also provides socio-economic benefits, including diversified income sources for farmers and improved food security, which are essential for the resilience of local communities. By promoting agroforestry through training, incentives, and technical support, Rubavu City can enhance its environmental sustainability while supporting the livelihoods of its rural population.

4.4.4. Strengthening Enforcement of Environmental Regulations

Effective enforcement of environmental regulations is critical to achieving sustainable forest management in Rubavu City. Despite the existence of robust legal frameworks such as Rwanda's Organic Law on the Environment (2005) and the Ministerial Order determining the structure, powers, and functioning of the Rwanda Environment Management Authority (REMA), enforcement remains a challenge. Strengthening enforcement mechanisms will ensure that urban development projects comply with environmental regulations, particularly those related to forest conservation. This can be achieved through enhanced monitoring and evaluation processes, capacity building for enforcement agencies, and increased public awareness of environmental laws.

Internationally, enforcement of environmental laws has been recognized as a key factor in successful forest conservation. For instance, the Convention on Biological Diversity (CBD) emphasizes the need for effective legal and institutional frameworks to protect biodiversity, including forests. By aligning local enforcement efforts with international standards and best practices, Rubavu City can enhance its capacity to protect its forested areas from illegal activities such as logging and land encroachment, which are significant contributors to deforestation.

4.4.5. Incentivizing Community Participation in Forest Conservation

Community participation is essential for the successful conservation of forests in Rubavu City. Engaging local communities in forest management not only ensures the sustainability of conservation efforts but also empowers residents to take ownership of their natural resources.

Rwanda's Vision 2050 and the National Decentralization Policy emphasize the importance of community involvement in environmental management. By providing incentives such as financial support, technical assistance, and capacity-building programs, the government can encourage local communities to actively participate in reforestation, afforestation, and forest protection initiatives.

Furthermore, community-led conservation initiatives, such as the establishment of community forests, can significantly contribute to forest restoration efforts. International examples, such as the Participatory Forest Management (PFM) approach adopted in various countries, have shown that involving communities in forest management leads to more sustainable outcomes. By adopting similar approaches, Rubavu City can harness the local knowledge and commitment of its residents to protect and restore its forests, thereby ensuring the long-term sustainability of its urban environment.

4.4.6. Developing Sustainable Livelihood Alternatives

To reduce pressure on forested areas, it is essential to develop and promote sustainable livelihood alternatives for communities that rely on forests for their income. The ongoing urban expansion in Rubavu City has led to a decline in forest resources, impacting the livelihoods of those who depend on timber, fuelwood, and non-timber forest products. Providing alternative livelihood options, such as eco-tourism, sustainable agriculture, and small-scale enterprises, can help reduce the reliance on forests while improving the economic well-being of local communities. Rwanda's National Strategy for Transformation (NST1) emphasizes the need to diversify economic activities and create employment opportunities, which can be leveraged to promote sustainable livelihoods in forest-dependent communities.

In addition, international frameworks like the UN Sustainable Development Goals (SDGs) advocate for the promotion of sustainable economic growth and decent work, particularly in rural areas. By aligning with these global goals, Rubavu City can implement programs that not only protect forest resources but also enhance the socio-economic resilience of its population. This dual approach will contribute to the long-term sustainability of forest management efforts in the region.

4.4.7. Establishing Urban Green Spaces and Forest Buffers

The creation of urban green spaces and forest buffers is a strategic approach to mitigate the impact of urbanization on forested areas in Rubavu City. Onilude and Vaz (2021) emphasize that establishing urban green spaces and forest buffers is crucial for mitigating the adverse effects of urban sprawl, as these areas provide essential ecological benefits such as enhancing biodiversity, improving air quality, and reducing urban heat. Moreover, Urban green spaces, such as parks and community gardens, provide essential ecosystem services, including air purificationand recreational opportunities, which are increasingly important as the city expands. Urban Green Spaces and Forest Buffers areas are vital for building resilience against climate change in African cities as outlined by Anderson et al. (2022).

Rwanda's National Urbanization Policy (2015) supports the development of green infrastructure as part of sustainable urban planning, emphasizing the importance of integrating natural elements into urban landscapes.

Furthermore, international experiences, such as the concept of Green Belts, have demonstrated the effectiveness of such buffers in curbing urban sprawl and protecting natural habitats. By adopting similar practices, Rubavu City can ensure that urban growth is managed in a way that respects and preserves its surrounding natural environment. These green spaces and buffers will also contribute to the well-being of urban residents by providing accessible areas for recreation and relaxation, thus enhancing the overall quality of life in the city.

4.4.8. Promoting Education and Awareness on Forest Conservation

Education and public awareness are crucial components of any sustainable forest management strategy. Increasing awareness among residents of Rubavu City about the importance of forests and the ecosystem services they provide can foster a culture of conservation and environmental stewardship. Educational programs, campaigns, and community outreach initiatives can be used to inform the public about the consequences of deforestation, the benefits of sustainable forest management, and ways to actively participate in conservation efforts. According to Alule, Nuwategeka, and Oriangi (2023), promoting education and awareness on forest conservation is essential for fostering sustainable management practices, as local communities equipped with

knowledge about their forest resources are more likely to engage in conservation efforts that benefit both the environment and their livelihoods. Rwanda's Environmental Education for Sustainable Development Strategy (2010) highlights the role of education in promoting sustainable development and environmental conservation.

Furthermore, international frameworks like the United Nations Decade on Ecosystem Restoration (2021-2030) emphasize the importance of raising awareness and building knowledge to support ecosystem restoration efforts. By leveraging these educational initiatives, Rubavu City can create a well-informed and engaged community that actively participates in forest conservation. This increased public awareness can lead to greater support for conservation policies and a stronger commitment to protecting the city's natural resources for future generations.

4.4.9. Future Research Directions and Ongoing Monitoring for Urban Expansion Impacts on Forest Cover

Future research should focus on long-term monitoring of forest dynamics using advanced remote sensing technologies combined with ground-truthing efforts. This approach will help understand the enduring impacts of urban expansion on forest cover over extended periods. Studies could investigate changes in forest structure and biodiversity, and predict how continued urbanization might influence these factors. For instance, a longitudinal study by Hansen et al. (2013) demonstrated the effectiveness of satellite imagery in monitoring global forest cover changes, highlighting its potential for localized studies. Additionally, research should explore how urban expansion affects forest ecosystem services, such as air and water quality, and carbon sequestration. Models predicting the impacts of urbanization on these services can guide more sustainable urban planning strategies (Houghton et al., 2012).

Ongoing monitoring efforts are crucial for effectively managing forest resources amidst urban expansion. Regular satellite remote sensing can provide up-to-date information on forest cover changes and urban encroachment, as demonstrated by the European Space Agency's Sentinel-2 mission (ESA, 2020). Complementing this with ground-based surveys and community-based monitoring initiatives ensures data accuracy and fosters local engagement in conservation efforts. Ecological impact assessments should be conducted periodically to evaluate changes in species diversity and habitat quality, informing future management decisions (Wright et al., 2016).

By integrating these research and monitoring strategies, stakeholders can better address the challenges posed by urban expansion and work towards sustainable forest management in Rubavu City.

Chapter five: Conclusion and recommendations

5.1. Conclusion

This research investigated the impacts of rapid urban expansion on forest ecosystems in Rubavu City from 2000 to 2020, highlighting significant changes in land use and land cover. The study found a notable decrease in forested areas due to urban development, which has led to adverse environmental consequences such as the loss of biodiversity, increased vulnerability to natural hazards like landslides, and degradation of essential ecosystem services such as water regulation and erosion control. These impacts, in turn, affect the livelihoods of local communities and the overall environmental sustainability of the region.

The key drivers of this urban expansion include population growth, economic activities, and infrastructure development, which together exert increasing pressure on forest resources. Through interviews with local officials and community members, it became clear that while urban expansion supports economic development, there is a critical need to balance this growth with environmental conservation measures.

5.2. Recommendations

5.2.1. For the District of Rubavu:

Recommendation: Integrate Sustainable Urban Planning into District Development Strategies

- **Purpose**: Address the adverse effects of urban expansion on forest cover by promoting sustainable development practices.
- **Key Actions**: Incorporate green infrastructure, establish urban green spaces, and implement strict land-use policies to control urban sprawl and protect forest ecosystems.
- **Impact**: This will help reduce the environmental footprint of urbanization, ensuring that ecosystem services such as climate regulation, water purification, and air quality are preserved for future generations.

5.21. For the Rwanda Environment Management Authority (REMA)

Recommendation: Strengthen Environmental Conservation Programs

- **Purpose**: Protect and restore degraded forest areas while managing urban growth.
- **Key Actions**: Promote reforestation and afforestation initiatives, particularly in areas where forest loss has been most severe due to urban expansion. Encourage community participation in these conservation efforts to increase local ownership and success rates.
- **Impact**: This will help to enhance ecosystem resilience, reduce the risk of environmental hazards like landslides, and improve biodiversity conservation.

5.2.3. For the Local Community and NGOs

Recommendation: Promote Public Awareness and Community Engagement

- **Purpose**: Increase awareness of the importance of forest conservation among local communities and encourage sustainable practices.
- **Key Actions**: Implement educational programs and campaigns that highlight the benefits of forest conservation. Support local NGOs and community-based initiatives that focus on sustainable livelihoods, such as eco-tourism, which can alleviate pressure on forest resources.
- **Impact**: Enhanced public awareness will foster greater involvement in forest conservation efforts and contribute to sustainable urban development.

5.2.4. For Policymakers (Ministry of Environment, Rwanda Forestry Authority, etc)

Recommendation: Develop and Enforce Stronger Forest Protection Policies

- **Purpose**: Ensure the legal framework supports forest conservation even in the face of urban expansion.
- **Key Actions**: Strengthen existing forestry laws and regulations and enforce penalties for illegal logging and deforestation. Integrate forest conservation goals into national urban

planning frameworks, ensuring that urban growth does not come at the expense of valuable natural resources.

- **Impact**: Stronger legal frameworks and enforcement will help mitigate further loss of forest cover and protect critical ecosystem services.

By adopting these recommendations, Rubavu City can promote a balanced approach to development that accommodates economic growth while preserving its natural heritage for future generations.

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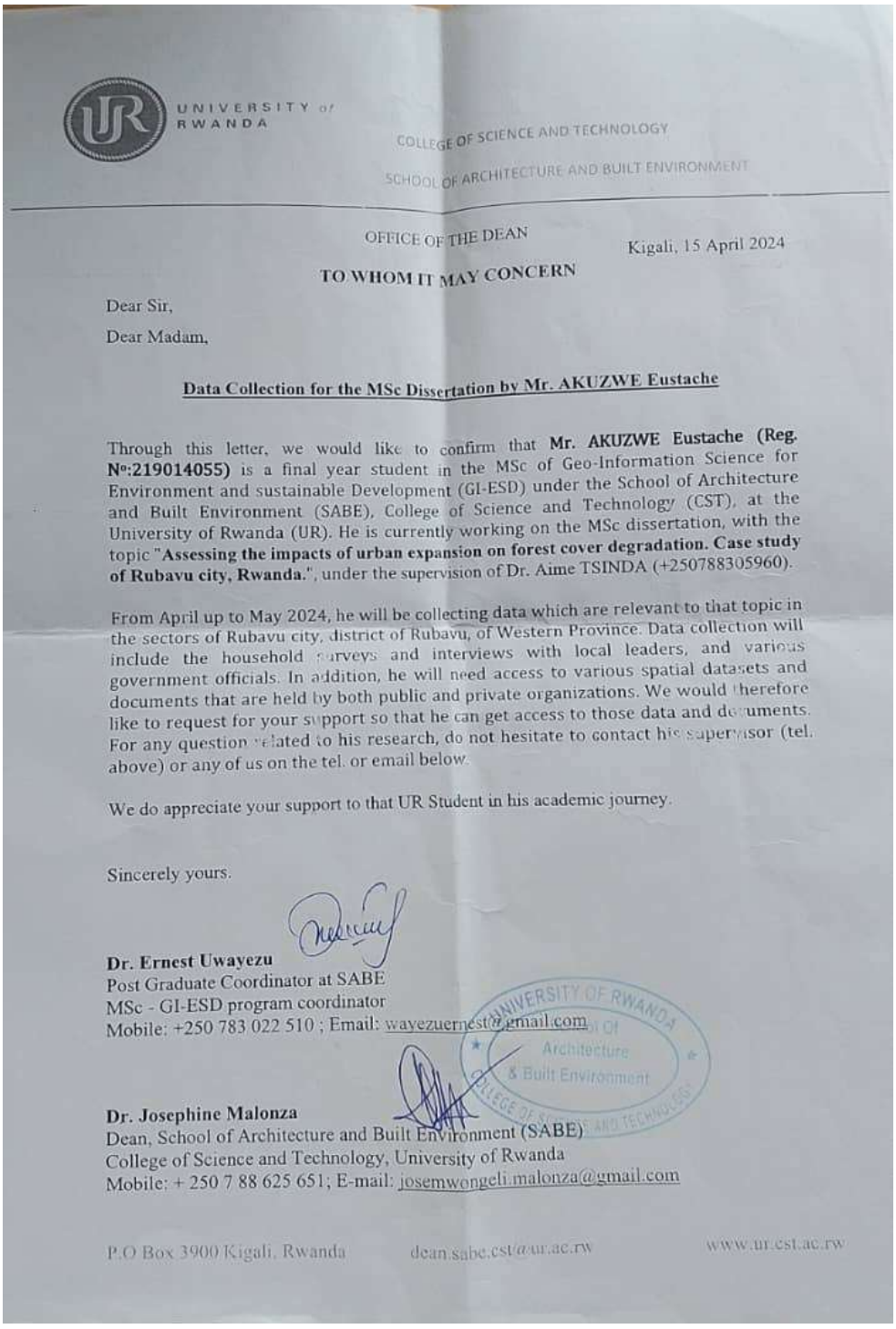
APPENDICES

Appendix 1: Data collection letter from University of Rwanda



UNIVERSITY of RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY

SCHOOL OF ARCHITECTURE AND BUILT ENVIRONMENT

OFFICE OF THE DEAN

Kigali, 15 April 2024

TO WHOM IT MAY CONCERN

Dear Sir,

Dear Madam,

Data Collection for the MSc Dissertation by Mr. AKUZWE Eustache

Through this letter, we would like to confirm that **Mr. AKUZWE Eustache (Reg. N°:219014055)** is a final year student in the MSc of Geo-Information Science for Environment and sustainable Development (GI-ESD) under the School of Architecture and Built Environment (SABE), College of Science and Technology (CST), at the University of Rwanda (UR). He is currently working on the MSc dissertation, with the topic "**Assessing the impacts of urban expansion on forest cover degradation. Case study of Rubavu city, Rwanda.**", under the supervision of Dr. Aime TSINDA (+250788305960).

From April up to May 2024, he will be collecting data which are relevant to that topic in the sectors of Rubavu city, district of Rubavu, of Western Province. Data collection will include the household surveys and interviews with local leaders, and various government officials. In addition, he will need access to various spatial datasets and documents that are held by both public and private organizations. We would therefore like to request for your support so that he can get access to those data and documents. For any question related to his research, do not hesitate to contact his supervisor (tel. above) or any of us on the tel. or email below.

We do appreciate your support to that UR Student in his academic journey.

Sincerely yours.

Dr. Ernest Uwayezu
Post Graduate Coordinator at SABE
MSc - GI-ESD program coordinator
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Letter granting permission for data collection

Republic of Rwanda
Western Province
Rubavu District

Ref: 544/03/03/ANR/24
Date: 14/05/2024

AKUZWE Eustache
0785030924
Baeustache@gmail.com

Dear AKUZWE

RE: Response to your letter

Reference is made to your letter of 24 April 2024 requesting to conduct research and data collection for the project entitled **"Assessing the impacts of urban expansion on forest cover degradation, case study Rubavu city"** and recommendation letter for data collection issued on 15 April 2024 University of Rwanda (UR), College of Art and Technology;

I am pleased to inform you that your request is granted and recommed you to submit a copy of your research findings (dissertation) to the District office once completed.

Sincerely,

AKARERE KA RUBAVU

RUHAMYA AMBUGA Olivier
District Executive Secretary

CC:

- Mayor of Rubavu District
- Executive secretary of Gisenyi, Rubavu, Nyamyumba, Rugerero, Nyundo, Nyakiriba and Kanama Sectors

Appendix 2: Questionnaire: Impact of Urban Expansion on Forest Cover and Ecosystem Services in Rubavu City

Introduction: Thank you for participating in this interview. Your insights are valuable in understanding the impacts of urban expansion on forest cover and ecosystem services in Rubavu City. The information gathered will contribute to the development of strategies for sustainable urban planning and forest conservation. Please answer the following questions based on your knowledge and experience.

Section 1: Respondent Information

1. **Name:**
2. **Position/Title:**
3. **Department/Organization:**
4. **Years of Experience in Current Role:**

Section 2: Urban Expansion in Rubavu City

5. **Can you describe the evolution of urban expansion in Rubavu City over the past two decades?**
    - Follow-up: What are the key drivers of this expansion?
6. **What areas of Rubavu City have experienced the most significant urban growth?**
    - Follow-up: Are there specific land use changes that have contributed to this growth?
7. **What are the primary factors influencing urban planning decisions in Rubavu City?**
    - Follow-up: How are environmental considerations, such as forest conservation, integrated into urban planning?

Section 3: Forest Cover Changes

8. **How has forest cover in Rubavu City and surrounding areas changed in the last 20 years?**
    - Follow-up: Are there any particular areas where forest loss has been most pronounced?
9. **What do you perceive as the main causes of deforestation or forest degradation in Rubavu City?**
10. **Have there been any efforts to reforest or restore degraded forest areas in Rubavu?**
    - Follow-up: Can you provide details on any specific projects or initiatives?

Section 4: Impacts of Urban Expansion on Ecosystems

11. **What are the observed or perceived impacts of urban expansion on local ecosystems, particularly on forest areas?**
    - Follow-up: How has this expansion affected biodiversity, water resources, and soil quality?
12. **What are the socio-economic consequences of changes in forest cover for the local population?**
    - Follow-up: How have these changes affected livelihoods, agriculture, and disaster risk (e.g., landslides, floods)?

Section 5: Ecosystem Services (ES)

13. **How has urban expansion impacted the provision of the following ecosystem services in Rubavu City?**

- **Water Supply:**
    - Has urban expansion affected the availability and quality of water resources?
    - Are there any challenges in maintaining water supply due to land use changes?

- **Food Production:**
    - Has agricultural land been affected by urban growth?
    - What impacts have been observed on local food production?
- **Raw Material:**
    - How has the availability of raw materials (e.g., timber, fuelwood) changed with urban expansion?
- **Erosion Control:**
    - What impacts has urban expansion had on soil erosion and sediment control?
- **Climate Regulation:**
    - How has the expansion of urban areas influenced local climate conditions, including temperature and precipitation?
- **Disturbance Regulation:**
    - What are the impacts of urban expansion on the ability of ecosystems to buffer against natural disturbances like floods?
- **Nutrient Cycling:**
    - How have nutrient cycles (e.g., carbon, nitrogen) been affected by changes in land use?
- **Pollination:**
    - Are there concerns about the decline of pollinators due to urbanization?
- **Recreation:**
    - Has the availability of natural areas for recreation been impacted by urbanization?
- **Cultural:**
    - Are there any cultural or spiritual values associated with forests that have been affected by urban growth?

14. **Which ecosystem services do you consider most vulnerable to the impacts of urban expansion in Rubavu City?**
    - Follow-up: What measures could be implemented to protect or restore these services?

Section 6: Mitigation Measures

15. **What current mitigation measures are in place to address the impacts of urban expansion on forest cover and ecosystem services in Rubavu City?**
    - Follow-up: How effective have these measures been?
16. **What role do local communities play in forest conservation and urban planning?**
    - Follow-up: Are there any community-led initiatives that have been particularly successful?
17. **What additional strategies do you think could be implemented to protect and restore forest areas and ecosystem services in Rubavu?**
    - Follow-up: What support is needed from the government or other organizations to implement these strategies?

Section 7: Policy and Regulation

18. **Are there existing policies or regulations that support the conservation of forests and ecosystem services in urban areas?**
    - Follow-up: How well are these policies being enforced in Rubavu City?
19. **What recommendations do you have for improving policies and regulations to better balance urban development with forest and ecosystem service conservation?**

Section 8: Conclusion

20. **In your opinion, what are the key challenges and opportunities for achieving sustainable urban development in Rubavu City?**
21. **Do you have any additional comments or suggestions on how Rubavu City can manage urban expansion while protecting its natural resources and ecosystem services?**

Thank you for your participation. Your responses will contribute significantly to this research and to the future planning efforts in Rubavu City.

Appendix 3: Land Use Land Cover Change

LULC Type	**2000 Area (Sq. Km)**	**2000 Percentage (%)**	**2010 Area (Sq. Km)**	**2010 Percentage (%)**	**2020 Area (Sq. Km)**	**2020 Percentage (%)**
Built-up	5.09	10.47	14.27	29.36	23.22	47.77
Forest	20.17	41.5	12.18	25.06	9.66	19.88
Agricultural land	16.1	33.12	10.5	21.6	13.26	27.28
Bare land	7.25	14.91	11.66	23.99	2.46	5.06
Total	48.59	100	48.59	100	48.59	100

Appendix 4: Forest and non-forest land cover in Rubavu city, 2000 to 2020

Classes	2000		2010		2020	
	Area in Sq.Km	**Percentage**	**Area in Sq.Km**	**Percentage**	**Area in Sq.Km**	**Percentage**
Forested Area	20.17	41.51	12.18	25.07	9.66	19.88
Non-Forested Area	28.42	58.49	36.41	74.93	38.93	80.12
Total Area	48.59	100.00	48.59	100.00	48.59	100.00

Appendix 5: Forest Ecosystem services estimation (USD ha^{-1} yr^{-1})

Forest System Services (ES)	Estimated coeffient (USD ha^{-1} yr^{-1}) by Kindu et al. (2016)	Forest Land (USD ha^{-1} yr^{-1}) ESV 2000	Forest Land (USD ha^{-1} yr^{-1}) ESV 2010	Forest Land (USD ha^{-1} yr^{-1}) ESV 2020
Water supply	8	161.36	97.44	77.28
Food production	32	645.44	389.76	309.12
Raw material	51.24	1033.5108	624.1032	494.9784
Genetic resources	41	826.97	499.38	396.06
Water regulation	6	121.02	73.08	57.96
Water treatment	136	2743.12	1656.48	1313.76
Erosion control	245	4941.65	2984.1	2366.7
Climate regulation	223	4497.91	2716.14	2154.18
Biological control	0	0	0	0
Gas regulation	13.68	275.9256	166.6224	132.1488
Disturbance regulation	5	100.85	60.9	48.3
Nutrient cycling	184.4	3719.348	2245.992	1781.304
Pollination	7.27	146.6359	88.5486	70.2282
Soil formation	10	201.7	121.8	96.6
Habitat/refugia	17.3	348.941	210.714	167.118
Recreation	4.8	96.816	58.464	46.368
Cultural	2	40.34	24.36	19.32
Total ES value		19901.5373	12017.8842	9531.4254

Source: Adapted from Kindu et al. (2016) and Negussie et al. (2019)