

**IMPACT OF LAND USE AND LAND COVERCHANGES ON CARBON
STOCKS IN SERERE'S CENTRAL FORESTS RESERVES.**

By

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(BU/GS20/MCC/16)

**A DISSERTATION SUBMITTED TO THE DIRECTORATE OF GRADUATE
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REQUIREMENT FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE
IN CLIMATE CHANGE AND DISASTER MANAGEMENT OF BUSITEMA
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CENTRAL FORESTS RESERVES. LAND USE AND**

Samuel Okurut

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**A dissertation submitted to the Directorate of Graduate Studies, Research and
Innovation in partial fulfillment of the requirement for the award of Master of Science
in Climate Change and Disaster Management Degree of Busitema University**

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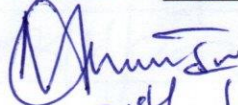
DECLARATION

I, Samuel Okurut, declare that this research report entitled: "Impact of Land use and land Cover changes on Carbon stocks in the Serere's Central Forest Reserves, Uganda" is my original work and has not been submitted for any academic award in any university or institution of higher learning. Where other people's work has been used, it has been properly acknowledged and referenced in accordance with academic rules and conventions.

This report is submitted in partial fulfillment of the requirements for the award of Master of Science in Climate Change and Disaster Management degree of Busitema University.

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APPROVAL

This is to certify that this research report entitled: "Impact of Land use and land cover Changes on Carbon Stocks in the Serere Central Forest Reserve, Uganda" has been written under our supervision and is solely the original work of the candidate, Samuel Okurut. The report contains authentic work of academic value and has been prepared following the University's approved research and formatting guidelines.

We therefore approve that this report be submitted for examination in partial fulfillment of the requirements for the award of the degree of Master of Science in Climate Change and Disaster Management of Busitema University.

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Date: _____

DEDICATION

This research work is dedicated to my beloved mother, Mrs. Oluka Anna Achipa, for her sacrificial heart and ceaseless prayers that have guided me through life.

To my dear wife, Mrs. Amulen Rhoda, whose unwavering support and encouragement have been the backbone of my academic journey, I extend my deepest gratitude. Special appreciation goes to my brothers, Mr. Oreta Andrew and Mr. Aogon Patrick, for their consistent reminders and motivation to accomplish this Master's program. I also dedicate this work to my friend and colleague, Mr. Ojelel Benjamin, for his selfless support and commitment in standing in for me at the workplace whenever duty called.

Lastly, this work is dedicated to my friends and classmates: Kaduuma Antony, Kakaire Victoria, Okello Moses, Bakole Alex, and Sam Paul Akol whose support, encouragement, and camaraderie have been invaluable throughout this academic journey.

May this piece of work reflect the sacrifices you all made.

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LIST OF ACRONYMS

AFOLU	Agriculture, Forestry and Other Land Uses
AGB	Above Ground Biomass
BGB	Below Ground Biomass
CC	Climate Change
CCD	Climate Change Department
CFM	Collaborative Forest Management
CO ₂	Carbon Dioxide
DOM	Dead Organic Matter
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
GIS	Geographic Information System
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPCC	Intergovernmental Panel on Climate Change
KNN	K-Nearest Neighbour
LiDAR	Light Detection and Ranging
LULC	Land Use and Land Cover
Mg C	Megagrams of Carbon
MLC	Maximum Likelihood Classifier
MWE	Ministry of Water and Environment
NDC	Nationally Determined Contributions
NEMA	National Environment Management Authority
NFA	National Forestry Authority
QGIS	Quantum Geographical Information Systems
REDD+	Reducing Emissions from Deforestation and Forest Degradation
RF	Random Forest
SCFRs	Serere's Central Forest Reserves
SOC	Soil Organic Carbon
SVN	Support Vector Machine
UBOS	Uganda Bureau of Statistics
UNFCCC	United Nations Framework Convention on Climate Change

ABSTRACT

This study assessed the impact of land use and land cover (LULC) changes on carbon stocks in Serere Central Forest Reserves, Uganda, between 2001 and 2020. Multi-temporal Landsat imagery was classified using the Random Forest algorithm in R and QGIS to map LULC transitions, and carbon stocks were estimated with the InVEST model using IPCC Tier 1 carbon density values. Boxplots illustrated carbon stock distributions across land use types over the years, while Spearman's rank correlation quantified the relationship between forest area and total carbon, and Kruskal–Wallis tests evaluated temporal differences in carbon stocks. The results revealed substantial LULC transformations, with forest cover declining from 22.73 km² (55.2%) in 2001 to 12.12 km² (29.4%) in 2020 a net loss of 10.61 km² while agricultural land expanded from 8.04 km² to 22.78 km² and settlements increased by 288 hectares. Total carbon stocks decreased by 36.9%, from 774,947 Mg C in 2001 to 488,991 Mg C in 2020, corresponding to approximately 1.05 million tonnes of CO₂ emissions. Forest areas accounted for the highest carbon losses (269,542 Mg C), whereas agricultural expansion contributed modest carbon gains (68,508 Mg C) due to its low carbon density. Spearman's correlation confirmed a strong, positive, and statistically significant relationship between forest area and total carbon stocks ($r_s = 0.986$, $p < 0.01$), highlighting forests as the primary determinant of landscape carbon dynamics. The Kruskal–Wallis test indicated no significant differences in carbon stocks across years, suggesting gradual rather than abrupt temporal changes. These findings underscore that deforestation and land conversion substantially reduce carbon storage capacity releasing more carbon to the atmosphere increasing the greenhouse gases and contributing to climate change, emphasizing the need for integrated land use planning, forest conservation, and community-based reforestation. The study provides empirical evidence to support Uganda's REDD+ initiatives and informs national strategies for climate change mitigation and resilience.

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Forests play a crucial role in regulating the global climate by acting as carbon sinks that absorb and store carbon dioxide (CO₂) from the atmosphere. Globally, forests sequester an estimated 662 billion tons of carbon, primarily in vegetation, soils, and biomass (IPCC, 2019). However, land use and land cover (LULC) dynamics significantly influence ecosystem functioning and directly impact the concentration of atmospheric CO₂ (Arias et al., 2021). Changes in land cover, especially through deforestation, forest degradation, agricultural expansion, and urbanization, have become major drivers of greenhouse gas (GHG) emissions globally (FAO, 2020; Rizvi & van Riel, 2021).

Anthropogenic activities have altered natural carbon fluxes, intensifying climate change impacts (Arias et al., 2021). The Agriculture, Forestry, and Other Land Use (AFOLU) sector alone contributed approximately 23% of total net anthropogenic GHG emissions between 2010 and 2019 (Jia et al., 2019). Among terrestrial ecosystems, tropical forests hold about 55% of global forest carbon and offer vital ecosystem services such as climate regulation and biodiversity conservation (Pan et al., 2011). Yet, these forests are under constant threat from land use change and human development pressures. Land use and land cover (LULC) change is one of the most pressing environmental challenges in Uganda and globally, threatening ecological integrity, biodiversity, and the ability of ecosystems to sequester carbon (IPCC, 2019).

In developing countries, particularly in sub-Saharan Africa, LULC change remains a major environmental concern. Forest landscapes are increasingly being transformed due to growing population pressure, agricultural intensification, and unsustainable land management practices (Lambin et al., 2003; Hosonuma et al., 2012). Uganda, like many tropical nations, has experienced rapid forest degradation and deforestation. Forest ecosystems are key in mitigating climate change by acting as carbon sequestrators (IPCC, 2019). However, Anthropogenic activities such as agricultural expansion, deforestation, and infrastructure development have altered land use and land cover (LULC), causing carbon stock losses and escalating greenhouse gas emissions (FAO, 2020). Uganda's emissions have had a steady rise, increasing from 53,000 Gg tonnes in 2005 to close to 90,000 Gg tonnes in 2015. The AFOLU sector has remained the most significant source, accounting for over 86% of the emissions, followed by the energy

sector contribution (MWE CCD, 2019). Uganda is ranked among the top 20 on the global list of tropical countries emitting carbon from deforestation (H. Gibbs et al., 2007; Hufty & Haakenstad, 2011). Deforestation, subsequent intensification of land use, and land degradation in Uganda have resulted in a decline in forest cover from 24% in 1990 to 12.4% in 2021 (NFA, 2021).

In Uganda, the increasing population, currently estimated at 45.9 million, up from 34.6 million in 2014, is exerting immense pressure on land resources for food production, settlement, and infrastructure development (UBOS, 2024). Agriculture, which sustains over 62% of the population, remains the leading driver of land conversion. Forests, wetlands, and grasslands are increasingly cleared to meet rising food and cash crop demands (NEMA, 2021; UBOS, 2024). The country lost approximately 63% of its forest cover between 1990 and 2015, primarily due to agricultural encroachment and biomass energy demand (NFA, 2016; MWE, 2019). This forest loss directly undermines the country's capacity to sequester carbon and adapt to climate-related risks.

Forests in Uganda form a critical part of the country's natural capital, supporting livelihoods, economic development, and ecological stability (NFA, 2021). However, the combined effects of deforestation, unsustainable land management, and infrastructural expansion continue to erode their carbon storage capacity and ecological integrity. Land use and land cover changes, in particular, have been shown to influence both the rate and spatial distribution of carbon storage and emissions (Rizvi & van Riel, 2021).

The Serere's Central Forest Reserves (SCFRs), located in Eastern Uganda, exemplify these challenges. Historically, this landscape has supported biodiversity conservation, timber production, and ecosystem services, including climate regulation, carbon storage, and local livelihoods. However, recent land cover transitions in the area, such as forest to agriculture conversions, pose serious threats to these functions (Turyahabwe et al., 2013). Despite this, there remained limited empirical evidence documenting the scale of LULC changes, the extent of carbon stock loss, or the nature of interactions between these variables in the Serere's Central Forest reserves landscape.

This gap can be addressed by assessing the impact of LULC changes on carbon stocks in the Serere's Central Forest Reserves over the past two decades. This could be achieved by describing the trends and spatial patterns of LULC changes, quantifying carbon stock dynamics over time, and determining the statistical relationship between LULC types and carbon stock

levels. Geospatial tools such as QGIS, R, and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model can be used to generate spatially explicit insights.

By examining the trends and relationships between LULC dynamics and carbon stocks, such study would generate knowledge critical for evidence-based policy formulation, forest conservation, and sustainable land management. The findings would support Uganda's climate commitments under the updated Nationally Determined Contributions of United Nations Framework Convention on Climate Change (UNFCCC) and other related agreements, while providing practical guidance to natural resource managers, policymakers, and researchers working to safeguard the carbon and ecological integrity of the Serere Central Forest Reserves.

1.2 Problem statement.

Forest landscapes in dry tropical regions are vital carbon sinks that play a crucial role in mitigating climate change by sequestering and storing atmospheric carbon, while simultaneously supporting biodiversity, regulating water cycles, maintaining soil fertility, and sustaining rural livelihoods. In Uganda, forests are central to climate regulation and socioeconomic well-being, yet they face escalating pressures from unsustainable human activities, including agricultural expansion, settlement development, charcoal production, and illegal logging, which have led to widespread forest degradation, significant loss of carbon stocks, and increased greenhouse gas emissions (FAO, 2020; NEMA, 2021). Nationally, forest cover declined from 24% in 1990 to 12.4% in 2021, driven by weak enforcement of environmental policies, population growth, and the growing demand for agricultural land (NFA, 2021; UBOS, 2021). The Serere Central Forest Reserves are particularly vulnerable, given their proximity to expanding rural settlements and high dependence of local communities on forest resources. This degradation undermines the forest's carbon storage capacity, impeding Uganda's fulfillment of international climate commitments under the UNFCCC and REDD+, as well as national objectives outlined in Vision 2040 and the National Development Plan IV, which emphasize sustainable natural resource management, climate resilience, and emission reductions. Beyond the national scale, forest loss in Serere also threatens regional and global goals, including the East African Community and African Union Agenda 2063, and Sustainable Development Goals 13 (Climate Action), 15 (Life on Land), and 2 (Zero Hunger) (UN, 2015). Despite the severity of these pressures, empirical evidence quantifying how land use and land cover (LULC) changes affect carbon stocks in Serere is limited, particularly regarding the magnitude, spatial patterns, and socio-economic drivers of carbon loss. Without such data, effective interventions for sustainable forest management, reforestation, and climate

resilience remain inadequately informed. Therefore, this study seeks to assess the impacts of LULC changes on carbon stocks over time, providing critical evidence to guide conservation strategies, inform policy, and support Uganda's national and international climate mitigation and adaptation commitments.

1.3 Objectives.

1.3.1 Main objective

The main objective of the study was to assess the impact of land use and land cover changes on carbon stocks in the Serere's Central Forest reserves.

1.3.2 Specific objectives

The specific objectives of the study were:

- I. To analyze the temporal trends and spatial patterns of land use and land cover changes in the Serere's Central Forest Reserves over the past 20 years.
- II. To evaluate changes in carbon stocks within the Serere's Central Forest Reserves overtime.
- III. To determine the relationship between land use and land cover changes and variations in carbon stock in the Serere's Central Forest Reserves.

1.4 Research questions

- I. What were the temporal trends and spatial patterns of land use and land cover changes in the Serere's Central Forest Reserves over the past 20 years?
- II. How had carbon stocks within the Serere's Central Forest Reserves changed during the study period?
- III. What is the relationship between land use and land cover changes and variations in carbon stocks within the Serere's Central Forest Reserves?

1.5 Justification of the study

This study is justified by its ability to fill knowledge gaps in the relationship between LULC changes and carbon stocks in Serere's Central Forest reserves. The findings will provide a scientific basis for informed decision-making, contributing to Uganda's commitments to international frameworks such as the United Nations Framework Convention on Climate Change (UNFCCC) through Nationally Determined Contributions (NDCs). Additionally, the study aligns with Uganda's Vision 2040, National Climate Change Act, and National Climate

Change Policy 2015, which emphasize sustainable land use management and ecosystem restoration to combat climate change. By providing actionable insights, this research will contribute to sustainable forest management, improved carbon sequestration, and long-term climate resilience in the Serere's Central Forest Reserves landscape and beyond.

1.6 Significance of the study

This study will add to early studies on the assessment of land use and land cover dynamics and the associated impacts on the carbon stocks. This study will provide information on the impact of changing the land use and land cover. It details how the conversion of forested areas to agricultural land impacts the carbon budget, and it will also provide an analysis of the conversion of forests to mono-dominant crop plantation and their impacts on the carbon cycle. Understanding the magnitude of possible effects of land use and land cover change on carbon stocks and land degradation is not only scientifically important, but it is also important for the development of a sustainable land use policy on ecosystem management that will anchor Nature-based Solutions for the mitigation and adaptation to climate change. This study will reveal how important it is to maintain the natural forests, grasslands, and wetlands crucial for the development of the management plans of the rangelands.

1.7 Conceptual framework

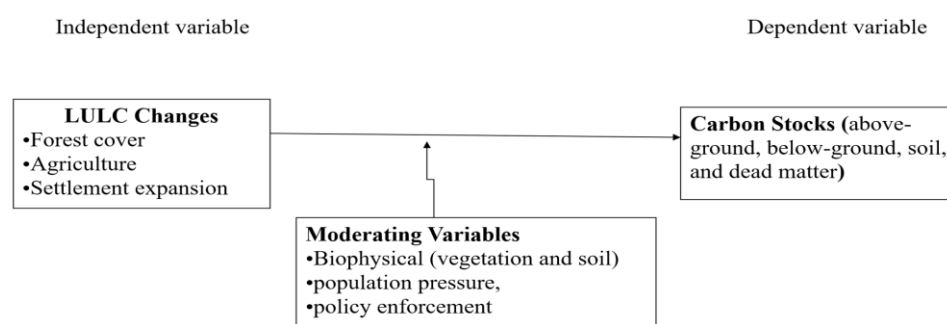


Figure 1: Conceptual Framework: adapted from the Ecosystem Services Theory (Costanza et al., 1997; Daily, 1997)

The conceptual framework for this study is based on the understanding that land use and land cover (LULC) changes directly influence the level and spatial distribution of carbon stocks

within forest ecosystems. Forests act as carbon sinks by storing carbon in above-ground biomass, below-ground biomass, soil, and dead organic matter. When forests are converted into other land uses such as agriculture or settlements, the carbon stored in vegetation and soils is often released into the atmosphere, contributing to greenhouse gas emissions and reducing the ecosystem's carbon sequestration potential.

The framework postulates that changes in land cover types such as a decline in forest area and increases in agriculture or built-up areas result in changes in carbon stock levels. These changes are influenced by both biophysical factors (e.g., vegetation type, soil characteristics) and anthropogenic factors (e.g., population pressure, agricultural expansion, policy enforcement).

CHAPTER TWO: LITERATURE REVIEW

2.1 Land use and land cover changes

Land use and land cover change (LULC) is a global phenomenon influenced by socio-economic, political, and environmental factors (Lambin et al., 2003). Deforestation and forest degradation are key drivers of LULC in tropical regions, primarily caused by agricultural expansion, logging, and settlement development (Hosonuma et al., 2012). These changes alter

the landscape structure and function, affecting biodiversity and ecosystem services. Land use and land cover (LULC) change represents a significant driver of global environmental change, influencing biodiversity, water availability, soil fertility, and climate regulation (Lambin et al., 2003). Land use refers to the human utilization of land (e.g., agriculture, forestry, settlements), whereas land cover denotes the physical and biological surface features of the earth (e.g., forest, grassland, urban areas) (Turner et al., 2007). The dynamics of LULC are shaped by interactions between socio-economic, demographic, technological, and institutional forces and have profound implications for the sustainability of ecosystems.

Globally, forests are being converted at alarming rates due to agricultural expansion, infrastructural development, and urbanization. The Food and Agriculture Organization (FAO, 2020) reports that the world lost 420 million hectares of forest between 1990 and 2020. Much of this loss occurred in the tropics, where forests are increasingly fragmented and replaced by cropland and settlements. These changes alter landscape structure, disrupt ecological functions, and reduce ecosystem services such as carbon sequestration and water regulation.

2.1.1 LULC change in Africa and Uganda

In Africa, the problem of LULC change is particularly acute due to high population growth, weak land governance, and economic dependence on natural resources. According to Hosonuma et al. (2012), the primary drivers of deforestation in sub-Saharan Africa include agricultural expansion, fuelwood extraction, and infrastructural development. The Intergovernmental Panel on Climate Change (IPCC, 2019) also notes that land degradation and forest conversion are accelerating in Africa, contributing significantly to biodiversity loss and greenhouse gas emissions.

Uganda exemplifies these challenges. The country has seen rapid population growth, with the Uganda Bureau of Statistics (UBOS, 2021) estimating the population at 45.9 million in 2024, up from 34.6 million in 2014. This surge has increased demand for agricultural land, timber, and housing, leading to accelerated forest clearance and land degradation. In Uganda, LULC has been marked by significant forest loss, with estimates showing annual deforestation rates ranging from 1% to 2.6% in various forest reserves (Tumushabe et al., 2021). Agricultural encroachment remains the main cause of forest cover reduction, driven by population growth and the demand for arable land. Between 1990 and 2015, Uganda lost over 63% of its forest cover, and forest area declined from 24% in 1990 to just 12.4% in 2021 (NFA, 2021)

Forest reserves, which are meant to be protected, are not immune to these pressures. In Uganda, numerous studies have documented LULC changes within central forest reserves due to weak enforcement, illegal logging, and encroachment (Turyahabwe et al., 2013; Mugagga, 2015). The Serere Central Forest Reserves in Eastern Uganda are among the forest ecosystems experiencing degradation from charcoal burning, unsanctioned farming, and settlement expansion (NEMA, 2021). These changes compromise not only biodiversity but also the forests' role as carbon sinks and providers of ecosystem services.

Understanding the temporal trends and spatial patterns of such changes is crucial for effective planning and policy implementation. This requires accurate, consistent, and up to date land cover data that reflects ground realities.

2.1.2 Remote sensing and GIS for LULC analysis

Remote sensing has emerged as a powerful tool for monitoring LULC changes over large spatial and temporal scales. Satellite imagery from platforms like Landsat, Sentinel, and MODIS enables the classification of land cover types and detection of changes with high spatial accuracy and temporal frequency (Weng, 2012). The Landsat program, in particular, has provided a near-continuous archive of moderate resolution imagery since the 1970s, making it ideal for long-term landscape analysis.

Geographic Information Systems (GIS) are used to store, manipulate, and visualize spatial data, enabling the integration of satellite-derived land cover maps with ancillary data such as topography, population density, or road networks. Together, remote sensing and GIS provide a comprehensive framework for assessing the magnitude, rate, direction, and causes of LULC change (Lu et al., 2004).

Numerous studies have employed remote sensing and GIS to monitor land cover changes in Uganda. Mwanjalolo et al. (2018) used Landsat imagery to study LULC trends in the Mt. Elgon ecosystem and reported widespread forest to agriculture conversions. Mugagga (2015) analyzed the dynamics within central forest reserves and found that unregulated settlement expansion significantly contributed to deforestation. However, few studies have examined LULC changes in Serere's Central Forest Reserves which give out leases to private forest planters, particularly with the integration of robust machine learning techniques for classification accuracy.

LULC classification involves assigning pixels in a satellite image to land cover categories such as forest, water, grassland, and built-up areas. Supervised classification is a commonly used

technique where the analyst provides training data for known land cover types, which are then used to classify the entire image based on spectral signatures.

Traditional classifiers such as Maximum Likelihood Classifier (MLC), Support Vector Machines (SVM), and K-Nearest Neighbors (KNN) have been widely used. However, with the advent of big data and high-dimensional imagery, more advanced methods such as Random Forest (RF) have gained popularity for their high accuracy, ability to handle complex data structures, and robustness against overfitting.

Random Forest (RF) is an ensemble learning algorithm introduced by Breiman (2001) that builds multiple decision trees and combines their outputs to make a final prediction. In classification tasks, each tree votes for a class, and the class with the most votes becomes the model's prediction. RF is known for its high classification accuracy, efficiency in handling high-dimensional datasets, and ability to manage noise and missing values (Belgiu & Drăguț, 2016).

Random Forests have several advantages compared to the other machine learning tools namely; Studies have shown that RF outperforms traditional classifiers such as MLC and SVM in terms of overall accuracy and kappa coefficient (Pal, 2005; Rodriguez-Galiano et al., 2012), RF does not require assumptions about the distribution of input data, making it suitable for heterogeneous and complex landscapes like those in Uganda, RF provides measures of variable importance, which helps understand which spectral bands or indices contribute most to classification performance. The algorithm is robust against noisy training data and overfitting due to its ensemble nature.

Several recent studies in Africa have successfully applied RF for LULC mapping. Jia et al. (2014) used RF to classify multi-temporal imagery in Ethiopia and reported higher accuracy than other classifiers. Wang et al. (2020) applied RF in Kenya's Mau Forest and demonstrated that RF was effective in distinguishing between forest degradation and conversion. In Uganda, Zhang et al. (2017) used RF in Uganda to assess LULC changes and confirmed the algorithm's superior classification performance.

Despite these advances, few studies have applied RF specifically within the Serere Central Forest reserves. Its application in this study is timely and relevant, offering the potential for high-accuracy classification of multi-temporal imagery and reliable detection of LULC trends.

2.1.3 Temporal analysis of LULC change

Temporal analysis involves comparing LULC maps from different years to detect changes in land cover classes. Such analysis enables the calculation of metrics such as: Change matrices, indicating gains and losses among classes, Annual rate of change, showing how quickly land cover is transitioning, Hotspots of change, identifying areas undergoing rapid transformation.

These metrics are essential for understanding the drivers and consequences of LULC dynamics and for prioritizing conservation or restoration efforts. Singh (1989) emphasizes that temporal remote sensing data is ideal for detecting LULC change trajectories and evaluating land degradation risks. In Uganda, Mugagga (2015) and Mwanjalolo et al. (2018) employed multi-date imagery to reveal trends in forest loss and agricultural expansion over time.

2.2 Forests and Carbon stocks

Forests are critical carbon sinks, storing large amounts of carbon in biomass and soils (FAO, 2020). The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for estimating carbon stocks in different forest pools, including aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter (IPCC, 2006).

Carbon stock refers to the quantity of carbon contained in a 'pool', meaning a reservoir or system that can accumulate or release carbon (IPCC 2016), including above-ground biomass (AGB), below-ground biomass (BGB), dead organic matter (DOM), and soil organic carbon (SOC). Forests, particularly in tropical regions, play a significant role in global carbon cycling by acting as carbon sinks, sequestering large quantities of atmospheric carbon dioxide (CO₂) (IPCC, 2006). Globally, forests store approximately 662 billion tonnes of carbon, with tropical forests accounting for nearly 55% of this storage (Pan et al., 2011). Accurate quantification of carbon stocks is therefore essential for understanding carbon dynamics, informing climate mitigation strategies, and fulfilling obligations under international frameworks such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation).

Carbon sequestration is a key ecosystem service that directly contributes to climate change mitigation (IPCC, 2019). However, changes in land use and land cover (LULC) primarily through deforestation, degradation, and conversion of forests to other land uses significantly reduce carbon storage capacity (Gibbs et al., 2007). As such, the need to monitor and evaluate carbon stock changes over time has become a priority for both science and policy, especially in carbon-rich and biodiversity-sensitive landscapes like Uganda's forest reserves.

Carbon stocks are commonly categorized into four major pools: (a) Above-Ground Biomass (AGB): Includes all living vegetation above the soil (e.g., trees, shrubs). (b) Below-Ground Biomass (BGB): Refers to roots and other plant material below the soil surface. (c) Dead Organic Matter (DOM): Includes litter, fallen leaves, and dead wood. (d) Soil Organic Carbon (SOC): Represents the largest and most stable carbon pool, often comprising over 60% of total ecosystem carbon (FAO, 2020).

Various approaches are used to estimate carbon stock changes across these pools. Field-based methods involve direct measurement using forest inventory data and allometric equations (Brown, 1997). However, these are often labor-intensive, time-consuming, and costly when applied over large areas. As a result, remote sensing and modeling techniques have become the preferred method for broad-scale carbon stock assessments (Goetz et al., 2009).

2.2.1 Role of remote sensing and modeling

Remote sensing enables consistent, repeatable, and spatially explicit monitoring of forest cover changes and associated biomass dynamics. Satellite platforms such as Landsat, Sentinel, and MODIS have been widely used to estimate AGB and monitor LULC changes that influence carbon storage (Lu et al., 2016). These datasets, when integrated with geospatial models such as InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), enable spatial quantification of carbon stock changes over time.

The InVEST Carbon Storage and Sequestration model is one of the most widely used open-source tools for spatially estimating carbon stocks and emissions. It estimates carbon stored in the four pools and allows for scenario-based simulations of carbon gains or losses due to LULC transitions (Sharp et al., 2020). The model requires a LULC map, carbon pool coefficients for each land cover class, and spatial overlays to quantify total carbon at different time steps. It has been successfully applied in various contexts, including in tropical forests, wetlands, and agricultural landscapes (Sharma et al., 2018; Kogo et al., 2020).

2.2.2 Temporal Carbon stock changes in forest landscapes

Several studies have analyzed temporal trends in carbon stock changes linked to land cover dynamics. For instance, De Sy et al. (2019) conducted a global assessment showing that tropical deforestation led to a net carbon emission of approximately 4.8 Gt CO₂ annually between 2001 and 2015. Similarly, Pearson et al. (2014) found that converting forests to agriculture can reduce carbon stocks by up to 80% depending on the crop type and management practice.

In East Africa, Mugagga (2015) quantified carbon losses from central forest reserves in Uganda and reported significant declines in above-ground biomass due to illegal logging and encroachment. Mwanjalolo et al. (2018) also observed notable reductions in carbon stock across Uganda's Mt. Elgon ecosystem, attributing the changes to intensive smallholder agriculture and population pressure. However, few studies have provided detailed, spatially explicit carbon stock assessments specifically for Eastern Uganda, particularly within the Serere's Central Forest Reserves landscape.

Uganda has experienced a dramatic decline in forest cover over the last three decades, from 24% in 1990 to just 12.4% by 2021 (NFA, 2021). This decline has major implications for national carbon sequestration goals and biodiversity conservation. The country's Nationally Determined Contributions (NDCs) under the UNFCCC highlight the importance of forest conservation and reforestation to mitigate emissions from the land use, land use change, and forestry (LULUCF) sector.

The Agriculture, Forestry and Other Land Use (AFOLU) sector is responsible for an estimated 22% to 50% of Uganda's total GHG emissions (Dehmel et al., 2022). Projections show that without effective mitigation, these emissions could reach 122.2 Mt CO₂e by 2030 (UNFCCC, 2022). Therefore, quantifying carbon stock changes is not only critical for academic understanding but also vital for national climate accountability.

2.3 Relationship between LULC changes and Carbon stock

Empirical studies show a strong positive correlation between forest area and carbon stocks (Nabukalu et al., 2020). Deforestation leads to significant carbon losses, while afforestation and forest conservation contribute to carbon gains. Agricultural lands generally have much lower carbon densities compared to forests; thus, expansion of agriculture typically results in net carbon stock declines (Asare et al., 2017).

Land use and land cover (LULC) changes have emerged as one of the most significant drivers of carbon stock fluctuations globally, especially in forest ecosystems. Forests act as carbon sinks by absorbing atmospheric carbon dioxide (CO₂) and storing it in biomass, dead organic matter, and soil pools (IPCC, 2019). However, changes in land use and land cover through processes such as deforestation, afforestation, reforestation, and land degradation alter the carbon balance of terrestrial systems (Pan et al., 2011; Houghton & Nassikas, 2017). Quantifying and understanding the statistical and spatial relationship between LULC change

and carbon stock dynamics is therefore crucial for informing climate mitigation strategies, sustainable land use policies, and forest conservation planning.

The link between LULC and carbon stocks is grounded in ecological and biogeochemical principles. Different land cover types, forests, grasslands, wetlands, and croplands, store and cycle carbon in distinct ways (Guo & Gifford, 2002). Forests, for instance, generally store more carbon in above-ground biomass than agricultural lands or grasslands, while wetlands contribute significantly to soil carbon pools due to anaerobic decomposition (IPCC, 2019). Consequently, transitions from one land cover type to another, such as forest to agriculture, often result in carbon loss to the atmosphere, contributing to greenhouse gas (GHG) emissions (Gibbs et al., 2007).

The Agriculture, Forestry, and Other Land Use (AFOLU) sector is a major source of anthropogenic GHG emissions, accounting for approximately 23% of total global emissions from 2010 to 2019 (Jia et al., 2019). These emissions arise predominantly from deforestation, forest degradation, and soil carbon losses. Conversely, reforestation, improved agricultural practices, and ecosystem restoration can enhance carbon sequestration (Lal, 2004).

In Uganda, over 90% of land cover change is driven by agricultural expansion and biomass energy demand, which directly impacts the country's carbon storage capacity (NEMA, 2021). As forests are cleared for Agriculture, human settlements, or charcoal burning, substantial carbon is released into the atmosphere (Dehmel et al., 2022). The Serere Central Forest Reserves, located in a region facing intense land use pressure, are particularly vulnerable to such carbon losses.

2.3.1 Carbon pools and measurement techniques

The Intergovernmental Panel on Climate Change (IPCC) categorizes carbon stocks into five major pools: (I) Above-ground biomass carbon stored in tree trunks, branches, and foliage, (II) Below-ground biomass carbon in roots and subsurface plant materials, (III) Dead organic matter including litter and dead wood, (IV) Soil organic carbon a large and stable pool found in topsoil layers, and (V) Harvested wood products carbon retained in wood products outside forests (IPCC, 2006).

Changes in LULC can affect all these pools simultaneously. For example, converting forest to agricultural land typically leads to the near-total loss of above-ground biomass and a substantial decline in soil organic carbon over time (Don et al., 2011).

Measuring these changes often involves field-based inventory data, remote sensing, and modeling techniques. The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) carbon model, used in this study, is a widely recognized spatially explicit tool that estimates carbon stocks by assigning biomass and soil carbon values to land cover classes and comparing them across periods (Sharp et al., 2020). It simplifies complex carbon cycle dynamics into accessible outputs suitable for scenario analysis and policy planning.

2.3.2 Theoretical framework

The theoretical framework for this study on the Impact of Land Use and Land Cover Changes on Carbon Stocks in the Serere's Central Forest Reserve is grounded in two complementary bodies of theory: Ecosystem Services Theory and Land-Use / Forest Transition Theory. Ecosystem Services Theory explains the functional role and value of forest carbon as an ecosystem regulating service, while Land-Use Transition Theory explains the socio-economic processes that drive changes in land cover and use over time. Together these theories provide a socio-ecological basis for (a) quantifying changes in carbon stocks and (b) explaining the drivers of those changes.

a) Ecosystem services theory

Ecosystem services theory frames ecosystems as suppliers of goods and services that sustain human well-being. Forests supply multiple regulating services, of which climate regulation through carbon sequestration and storage is central (Daily, 1997; Costanza et al., 1997). Carbon is stored in aboveground biomass, belowground biomass, litter and dead organic matter, and soil organic carbon. Alterations to vegetation cover and soil disturbance thereby change the capacity of the landscape to sequester and store carbon (IPCC, 2021).

Treating carbon as an ecosystem regulating service focuses attention on how LULC transitions (e.g., forest → agriculture; forest → settlement) change the supply of that service. This theoretical lens justifies measuring carbon pools spatially and temporally, and valuing losses where relevant. It also motivates the combined use of remote sensing and field-based biomass/soil sampling or modelled approaches (e.g., InVEST) to estimate changes in ecosystem service supply.

Ecosystem services theory directly underpins Objective II (to evaluate changes in carbon stocks) because the objective measures a regulating service whose supply depends on vegetation and soil conditions altered by LULC change.

b) Land-use / Forest transition theory

The Land-Use or Forest transition theory describes the temporal sequence of land cover change that frequently accompanies socio-economic development: an early phase dominated by deforestation and agricultural expansion, potentially followed by stabilization and reforestation under particular economic, policy, or institutional conditions (Mather, 1992; Mather, 1998). Drivers include population pressure, agricultural intensification, market integration, migration, land tenure, and governance arrangements.

This theory provides a socio-economic explanation for observed LULC trajectories. Understanding whether the Serere's central Forest Reserves landscape is in an early deforestation phase or a later stabilization/recovery phase affects how we interpret carbon stock trends and which interventions might be effective. The theory highlights that carbon dynamics are tightly coupled to household livelihoods, market forces, institutional arrangements and policy environments.

Land-Use transition theory informs Objective I (to describe and map LULC changes) and Objective III (to identify drivers of change) by framing LULC as a socio-ecological outcome influenced by demographic, economic and institutional factors. It supports the use of household surveys, key informant interviews and secondary socio-economic data to link spatial patterns of carbon loss to human drivers.

When combined, Ecosystem Services Theory and Land-Use Transition Theory provide a robust framework for the present study: the former explains the ecological importance and measurement of carbon stocks, while the latter explains the socio-economic processes that generate LULC change. This integrated perspective justifies a mixed-methods approach: spatial analysis and carbon modelling (remote sensing + InVEST/biomass estimation) to quantify changes in carbon pools, and qualitative and quantitative socio-economic methods to identify and interpret drivers.

From the theoretical framework the study derives the following expectations and methods:

- i. Areas converted from forest to agriculture or settlement will show significant reductions in total carbon stocks (above- and belowground biomass plus soil carbon) compared to stable forest areas. Combine multi-temporal LULC maps (2001–2020) with biomass/soil carbon estimates derived from InVEST modelling.
- ii. Hotspots of forest loss and carbon decline are associated with socio-economic drivers such as agricultural expansion, population pressure, insecure tenure and weak local

governance; conversely, areas with stronger governance arrangements will show lower rates of carbon loss.

2.3.3 Empirical studies linking LULC and Carbon stocks

A growing body of literature has examined the relationship between LULC changes and carbon dynamics in different ecological zones. Globally, Pan et al. (2011) estimated that tropical forests hold approximately 55% of global forest carbon, highlighting their vulnerability to land conversion. In their global synthesis, Houghton & Nassikas (2017) found that tropical deforestation alone contributes nearly 1.5 billion tons of carbon emissions annually.

In East Africa, Chidumayo & Gumbo (2010) reported significant carbon stock losses due to land conversion from woodland to agriculture. Wang et al. (2020) used Landsat imagery and InVEST modeling to estimate that the Mau Forest in Kenya lost over 20% of its carbon stock due to agricultural encroachment between 2000 and 2015.

In Uganda, Mugagga (2015) assessed forest degradation and its implications for carbon storage in central reserves and found that charcoal production and subsistence farming significantly reduced above-ground carbon stocks. Turyahabwe et al. (2013) highlighted similar losses in the Budongo and Mabira forests, driven by unregulated land use and weak forest governance. However, studies directly linking LULC changes to carbon stocks using spatial and statistical models in Serere District remain limited, highlighting the relevance of the present research.

Quantifying the relationship between land use and land cover (LULC) and carbon stocks can be achieved using a variety of statistical approaches. In the present study, we employed Kruskal–Wallis rank sum tests, Spearman’s rank correlation, and boxplots to examine how carbon stocks vary across land use types and over time. The Kruskal–Wallis test allows for the comparison of carbon stocks across multiple years without assuming normality, revealing whether differences are statistically significant (Hollander et al., 2013). Spearman’s rank correlation assesses the strength and direction of monotonic relationships between land use areas and total carbon stocks, providing insights into which land uses drive carbon dynamics (Zar, 2010). Boxplots visually illustrate the distribution and variability of carbon stocks across land use types and years, enabling identification of temporal trends and differences in storage capacity.

The use of these non-parametric and exploratory tools is particularly suited to LULC and carbon data, which often exhibit skewed distributions and heteroscedasticity. For example, forested areas are expected to have high carbon stocks with greater variability, whereas

agriculture, settlements, bare land, and water typically show lower and more uniform carbon storage. By combining statistical testing with visualization, this approach provides both quantitative and interpretative understanding of how LULC changes influence carbon stocks over time (Jobbágy & Jackson, 2000; Pan et al., 2011).

The synergy between remote sensing and carbon modeling has transformed LULC carbon studies by providing time-series data that are spatially explicit and scalable. Landsat imagery is particularly valuable due to its consistent temporal archive, moderate spatial resolution (30 m), and compatibility with classification algorithms like Random Forest (Weng, 2012). Classified land cover maps can be used as inputs for models like InVEST, which estimate carbon content per class. Changes in class areas over time can then be directly translated into carbon gains or losses. This approach has been successfully applied in various forested landscapes, including Mt. Elgon, Uganda, where Mwanjalolo et al. (2018) used Landsat and InVEST to quantify forest-to-agriculture conversion impacts on carbon storage, and in the Amazon Basin, where Asner et al. (2010) mapped forest degradation and associated biomass loss using airborne LiDAR integrated with Landsat imagery.

By adopting this approach in Serere, the current study provides a spatially explicit and quantitative evaluation of how LULC dynamics have altered carbon stocks from 2001 to 2020.

Understanding how LULC changes influence carbon stocks is essential for designing mitigation strategies under frameworks such as the Nationally Determined Contributions to the UNFCCC, REDD+, Vision 2040, and the National Forest Plan (2013–2023). Forest ecosystems like those in Serere offer opportunities for nature-based solutions, but their effectiveness depends on robust empirical understanding of land-carbon interactions. Land use and land cover changes exert profound impacts on terrestrial carbon dynamics, particularly in tropical forested ecosystems. Empirical evidence consistently shows that deforestation and agricultural expansion lead to substantial carbon losses, while restoration and reforestation enhance carbon sequestration (Lal, 2005; Lewis et al., 2019).

In Uganda, where forest reserves such as Serere are under intense anthropogenic pressure, understanding the spatial and statistical relationships between LULC and carbon stocks is critical. By integrating satellite-derived land cover data, carbon modeling through InVEST, and non-parametric statistical analyses (Kruskal–Wallis, Spearman’s correlation, and boxplots), this study provides a robust framework for assessing these interactions. The findings support sustainable land use planning, climate mitigation strategies, and national development priorities by highlighting the critical role of forests in landscape carbon storage.

2.3.4 Limitations and gaps in existing literature

While carbon stock assessment has gained global attention, several challenges persist. First, many studies focus primarily on above-ground biomass, neglecting the contribution of soil organic carbon and dead organic matter to total ecosystem carbon. Second, spatial heterogeneity and landscape fragmentation are often not well accounted for, especially in diverse ecosystems like those found in Uganda. Third, there is limited longitudinal analysis of carbon trends at district or forest reserve level, particularly in underrepresented areas such as Serere District.

Moreover, the application of tools like InVEST in the Ugandan context remains limited, despite their suitability for assessing carbon stock changes in data scarce environments (Kogo et al., 2020). There is a need to localize and calibrate such models using Uganda specific carbon coefficients to improve result accuracy and policy relevance.

CHAPTER THREE: METHODOLOGY

3.1.1 Study area

The study was conducted in the Serere Central Forest Reserves, located within Serere District in the Eastern Region of Uganda. Serere District lies in the Teso sub-region, bordered by Ngora District to the north, Soroti to the northwest, and Kaberamaido to the west. Geographically, it is positioned between latitudes 1°30'N and 1°50'N, and longitudes 33°30'E and 33°50'E, occupying part of the Lake Kyoga basin.

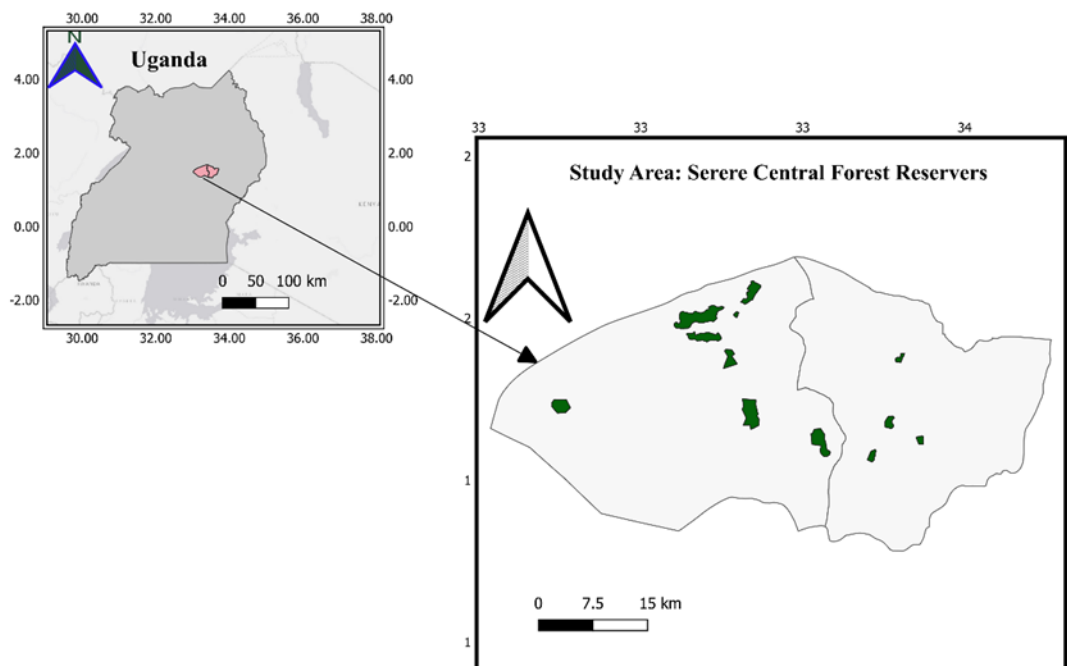


Figure 2: Location of Serere Central Forest Reserves

The forest reserves in Serere District are part of a network of gazetted central forest reserves managed by the National Forestry Authority (NFA). Though relatively small and fragmented in size, these forests are ecologically significant, providing a range of ecosystem services including carbon storage, biodiversity conservation, water regulation, and soil protection. The reserves also serve as important socioeconomic resources for local communities who depend on them for fuelwood, medicinal plants, construction materials, and cultural practices.

The area is characterized by flat to gently undulating terrain, with average elevations ranging between 1,050 and 1,100 meters above sea level. The dominant vegetation includes dry woodland savannah, grasslands, and patches of natural forest cover, interspersed with agricultural lands and settlements.

The climate of Serere is classified as tropical savannah (Aw) under the Köppen climate classification, with bimodal rainfall patterns. The first rainy season typically occurs from March to June, and the second from September to November, with total annual rainfall ranging between 1,000 mm and 1,300 mm. The average temperatures range between 20°C and 30°C throughout the year (NEMA, 2021).

Due to rapid population growth, agricultural expansion, and deforestation, the Serere Central Forest Reserve has been under increasing anthropogenic pressure. Activities such as charcoal production, illegal logging, and encroachment for crop farming have contributed to significant

land use and land cover (LULC) changes, threatening the ecological integrity and carbon sequestration potential of the forest landscape.

3.1.2 Scope of the study

The study focused on the impact of land use and land cover (LULC) changes on carbon stocks in the Serere's Central Forests Reserves Landscape encompassed several key dimensions.

Geographically, the study is confined to the Serere's Central Forest Reserves, located in Serere District, Eastern Uganda. This area has been selected due to its ecological significance and the increasing pressure from human activities such as deforestation, charcoal burning, agricultural encroachment, and settlement development.

Thematically, the research focuses on assessing the impact of land use and land cover (LULC) changes on carbon stock levels. It emphasizes forest ecosystems and their role in carbon sequestration, and how these functions are being influenced by changes in land use patterns over time.

Temporally, the study covers 20 years from 2001 to 2020. This duration allows for the detection of long-term trends and patterns in LULC dynamics and associated changes in carbon stocks. Data are analyzed at five-year intervals using satellite imagery from Landsat 5, 7 and 8.

Methodologically, the study applies a combination of remote sensing, Geographic Information Systems (GIS), and the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model to quantify and map changes in both land cover and carbon stocks. Supervised classification, particularly using the Random Forest Algorithm, is used for LULC mapping, while correlation is employed to assess the statistical relationship between LULC types and carbon stock levels.

3.2 Research design

This study employed a quantitative, spatial-temporal research design grounded in remote sensing, geospatial analysis, and statistical modeling to evaluate the impact of land use and land cover (LULC) changes on carbon stocks in the Serere Central Forest Reserves from 2001 to 2020. The design integrated satellite imagery analysis, supervised classification, field verification (ground-truthing), and carbon stock modeling, allowing for a comprehensive assessment of LULC transitions and their effects on carbon dynamics over two decades.

The research followed a retrospective longitudinal approach, analyzing multi-temporal satellite imagery at five intervals: 2001, 2005, 2010, 2015, and 2020. The year 2001 was selected in place of 2000 due to the absence of cloud-free imagery. Satellite images were acquired from the Landsat 5 (TM), Landsat 7 (ETM+), and Landsat 8 (OLI/TIRS) sensors, all with 30-meter spatial resolution, providing consistent data for temporal comparison (USGS, 2023).

3.2.1 Data preprocessing and image preparation

All imagery underwent atmospheric correction using the Semi-Automatic Classification Plugin (SCP) in QGIS to ensure radiometric consistency (Congedo, 2021). In cases where striping artifacts or incomplete scenes were observed (particularly in Landsat 7 imagery), de-striping techniques and mosaicking were applied to restore image quality. The corrected images were then raster-stacked by year, preparing them for classification (Chander et al., 2009).

3.2.2 Land use and land cover classification

The raster stacks were imported into R, where supervised classification was conducted using the Random Forest (RF) algorithm, implemented through the *terra* package (Hijmans, 2023). Training samples for different land use and land cover classes were manually digitized using Google Earth imagery, ensuring temporal correspondence with each Landsat scene. These training points were georeferenced and imported into R for model training and classification.

Random Forest was chosen due to its high classification accuracy, robustness to noise, and ability to handle non-linear class boundaries, making it ideal for complex, heterogeneous landscapes such as those found in the Serere Central Forest Reserves (Belgiu & Drăguț, 2016; Rodriguez-Galiano et al., 2012).

3.2.3 Ground truthing and accuracy assessment

To validate classification outputs, ground truthing was conducted for a sample of locations across the study area. These points were collected using handheld GPS devices and compared with classified maps to assess classification accuracy. Confusion matrices, overall accuracy, and Kappa statistics were calculated to evaluate the reliability of the land cover maps (Foody, 2002; Congalton & Green, 2009).

3.2.4 Carbon stock modeling

The classified land cover maps were used as input layers for carbon stock estimation using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model (Sharp et al., 2020). Land cover classes were assigned default carbon pool values (aboveground,

belowground, soil, and dead organic matter) based on IPCC Tier 1 guidelines and region-specific literature (IPCC, 2006; Saatchi et al., 2011). This enabled estimation of total carbon stocks for each land cover class across the five time points.

3.3 Data sources

This study utilized both primary and secondary data sources to assess the impact of land use and land cover (LULC) changes on carbon stocks in the Serere Central Forest Reserves over 20 years. The data were drawn from credible global repositories, field surveys, and scientifically validated literature to ensure accuracy, relevance, and spatial-temporal consistency.

Table 3:1 Data sources

Data Type	Source	Purpose/Use
Landsat 5 (TM), Landsat 7 (ETM+), Landsat 8 (OLI/TIRS)	United States Geological Survey (USGS)	Acquisition of satellite imagery for LULC classification (years: 2001, 2005, 2010, 2015, 2020)
Google Earth Imagery	Google Earth Pro	Generation of training samples and visual verification for LULC classification
Ground GPS Coordinates	Field survey (Ground truthing)	Validation of classification accuracy and LULC verification
Carbon Pool Values	IPCC Tier 1 Guidelines (IPCC, 2006); Saatchi et al. (2011)	Estimation of carbon stocks by LULC class in the InVEST model
LULC Classification Algorithms	R Statistical Software (`terra`, `random Forest` packages)	Classification of raster stacks using the Random Forest algorithm
InVEST Carbon Model	Natural Capital Project (Sharp et al., 2020)	Modeling and quantifying carbon stock storage and change over time

Administrative Boundaries	Uganda Bureau of Statistics (UBOS); NFA Shapefiles	Mapping and spatial reference for Serere Central Forest Reserves
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3.4 Data analysis

Data analysis involved an integrated approach combining remote sensing, spatial modeling, and statistical techniques to evaluate land use and land cover (LULC) changes and their effects on carbon stock dynamics between 2001 and 2020 in the Serere Central Forest Reserves. The analysis was conducted using QGIS 3.28, InVEST 3.9.0, and R version 4.3.1, following established environmental and statistical methodologies.

3.4.1 Changes in the land use and land cover overtime

Landsat imagery for 2001, 2010, and 2020 was pre-processed through atmospheric correction, mosaicking, and clipping to the study boundary using QGIS 3.28. Supervised classification was then performed in R using the Random Forest (RF) algorithm implemented in the “randomForest” package. The RF classifier was preferred for its high predictive performance and resistance to overfitting in complex spectral datasets (Belgiu & Drăguț, 2016; Pelletier et al., 2020). Training samples were derived from field data, high-resolution Google Earth imagery, and expert validation. LULC classes included forest, agricultural land, grassland, wetland, settlement, and bare land. Classification accuracy was evaluated using confusion matrices, and overall accuracy and Kappa coefficients were computed with the “caret” package (Congalton & Green, 2019).

Change detection was conducted by cross-tabulating classified LULC maps from 2001, 2010, and 2020 to determine the magnitude and spatial direction of transitions among classes. The rate and percentage of change were calculated following Weng (2002), while transition matrices were produced in R to quantify conversions between land cover categories. Spatial visualizations of deforestation, agricultural expansion, and settlement encroachment were generated in QGIS to highlight degradation hotspots across the study period.

3.4.2 Carbon Stock changes

Carbon stock estimation was carried out using the InVEST Carbon Storage and Sequestration Model (version 3.9.0), developed by the Natural Capital Project (Sharp et al., 2020). The model computes total carbon storage as the sum of four carbon pools; above-ground biomass, below-ground biomass, soil organic carbon, and dead organic matter parameterized using IPCC (2006) Tier 1 carbon density values. The total carbon stock for each land cover class was derived as:

$$C_{total} = (C_{AGB} + C_{BGB} + C_{SOC} + C_{DOM}) \times A$$

Where C_{total} is the total carbon stock (Mg C), C_{AGB} , C_{BGB} , C_{SOC} and C_{DOM} are carbon densities (Mg C/ha), and A represents the area (ha) of each LULC type. The difference in total carbon between 2001 and 2020 provided an estimate of carbon loss or gain across the landscape (Swetnam et al., 2022).

Statistical analysis was performed in R (version 4.3.1) to evaluate associations between LULC changes and carbon stock variations. Descriptive statistics, including mean, standard deviation, and percentage change, were computed using the “dplyr” and “tidyverse” packages.

3.4.3. Relationship between land use and carbon stocks

Descriptive statistics were first computed to summarize the central tendency and variability of carbon stock values across land use types. To assess whether there were significant differences in carbon stocks across years, a Kruskal–Wallis rank sum test was employed. This non-parametric test was selected over ANOVA because the data did not meet assumptions of normality and equal variances, making it more robust for small or skewed samples (Field et al., 2012). The test evaluated the null hypothesis that the median carbon stocks did not significantly differ across years.

To examine the strength and direction of relationships between land use types and total carbon stocks, a Spearman’s rank correlation test was performed. This non-parametric test was selected because it does not assume normality and is appropriate for monotonic relationships between ranked variables. The correlation was computed between total carbon stock and the area of each land use class (forest, agriculture, settlements, bare land, and water) across the study years.

The analysis was conducted in R (version 4.x) using the `cor.test()` function with `method = "spearman"`. The results were extracted and summarized using the `tidyverse` and `broom` packages to produce a compact table showing the correlation coefficient (ρ), p-value, and significance level ($p < 0.05$). Significance levels were denoted as follows: * = significant ($p < 0.05$), and ns = not significant ($p \geq 0.05$).

Visualization of carbon stock distribution was performed using box plots generated in the `ggplot2` package in R. These plots display the median, interquartile range, and potential outliers of carbon stocks by land use type for throughout the study period, providing an intuitive comparison of carbon stock variability and trends across time and land cover categories

The analyzed results were presented using maps, charts, and tables. LULC and carbon storage maps generated in QGIS and InVEST were used to display spatial distributions and temporal

trends. Graphical outputs such as boxplots, and bar charts were produced in R using ggplot2 to illustrate correlations and associations between LULC dynamics and carbon stocks. The visual outputs were designed to enhance interpretability, highlight carbon loss hotspots, and communicate results in a spatially explicit format (Gandhi et al., 2015; Sannier et al., 2021).

3.5 Ethical considerations

The study involved non-invasive techniques such as remote sensing and GIS analysis, which posed no physical harm to the forest ecosystem. Field validation activities were conducted responsibly, ensuring that no flora, fauna, or habitats were disturbed during the data collection process. Where possible, local knowledge was integrated to validate classification outputs. The research strictly followed principles of academic honesty and integrity. All secondary sources of data and literature were properly cited to avoid plagiarism. Analytical tools and methodologies used, such as QGIS, SCP, and the InVEST carbon model, were applied in accordance with scientific guidelines and best practices.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Land Use and Land Cover change in the Serere's Central Forest Reserves (2001–2020)

Analysis of multi-temporal Landsat imagery and classification results revealed significant changes in the landscape. The LULC classification maps derived from Random Forest supervised classification in QGIS and R indicated a marked reduction in forest cover and an expansion of cropland and settlements. Forest cover in the reserves showed a consistent and sharp decline over the study period, dropping from 22.73 Km² (55.2%) of the total area in 2001 to just 12.12 Km² (29.4%) in 2020, which translates to a loss of 10.61 Km² of forest cover over the study period.

In contrast, land under agriculture expanded from 8.04 Km² (19.5%) in 2001 to 22.78 Km² (55.33%) in 2020. Settlement areas also expanded significantly, increasing by 288 hectares

over the study period. These trends are consistent with findings by Naab et al. (2021), who reported rapid forest loss due to agricultural encroachment and population pressure in eastern Uganda.

Table 4:1 Summarizes the area (in square kilometers) and percentage of each land cover class for all the studied years

Year	Agric	%	Bare-Land	%	Forest	%	Settlements	%	Water	%
2001	804.24	19.5	3.65	8.9	22.73	55.2	5.88	14.3	0.87	2.1
2005	12.38	30.1	2.07	5.0	19.56	47.5	6.48	15.8	0.67	1.6
2010	14.53	35.3	3.08	7.5	18.62	45.2	4.86	11.8	0.07	0.2
2015	15.32	37.2	1.28	3.1	15.35	37.3	8.76	21.3	1.09	1.1
2020	22.78	55.3	0.86	2.1	12.12	29.4	5.32	12.9	0.21	0.2

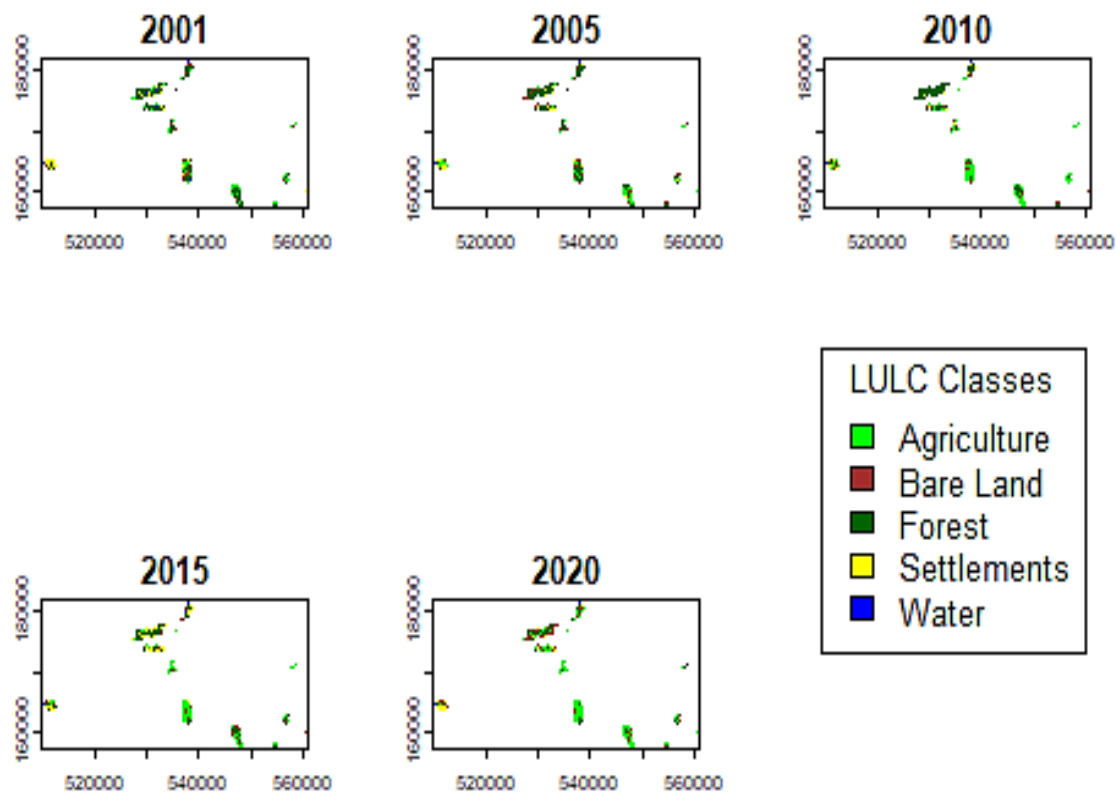


Figure 3: Spatial trends of Forest Cover in Serere Central Forest Reserve (2001–2020)

Classified raster maps for each year (Figure 3) present the spatial distribution of forest and other land cover types within the study area. Over time, areas previously dominated by forests are visibly converted into agricultural fields and settlements. The spatial consistency of land cover loss reinforces the findings from the tabular and graphical analyses.

These results are consistent with the overall Serere district land use and land cover changes over the study period. Below is the spatial representation of the district classified maps, which indicates an overall increase in agricultural land from 533.85 Km² (27.2%) in 2001 to 761.63 Km² (39.8%) in 2020. Settlements also expanded from 213 Km² to 285 Km². Overall, in the district, there is a slight increase in the forest land attributable to plantation forests not captured in this study from 252.2 Km² to 434.1 Km².

4.2 Changes in Carbon stocks overtime

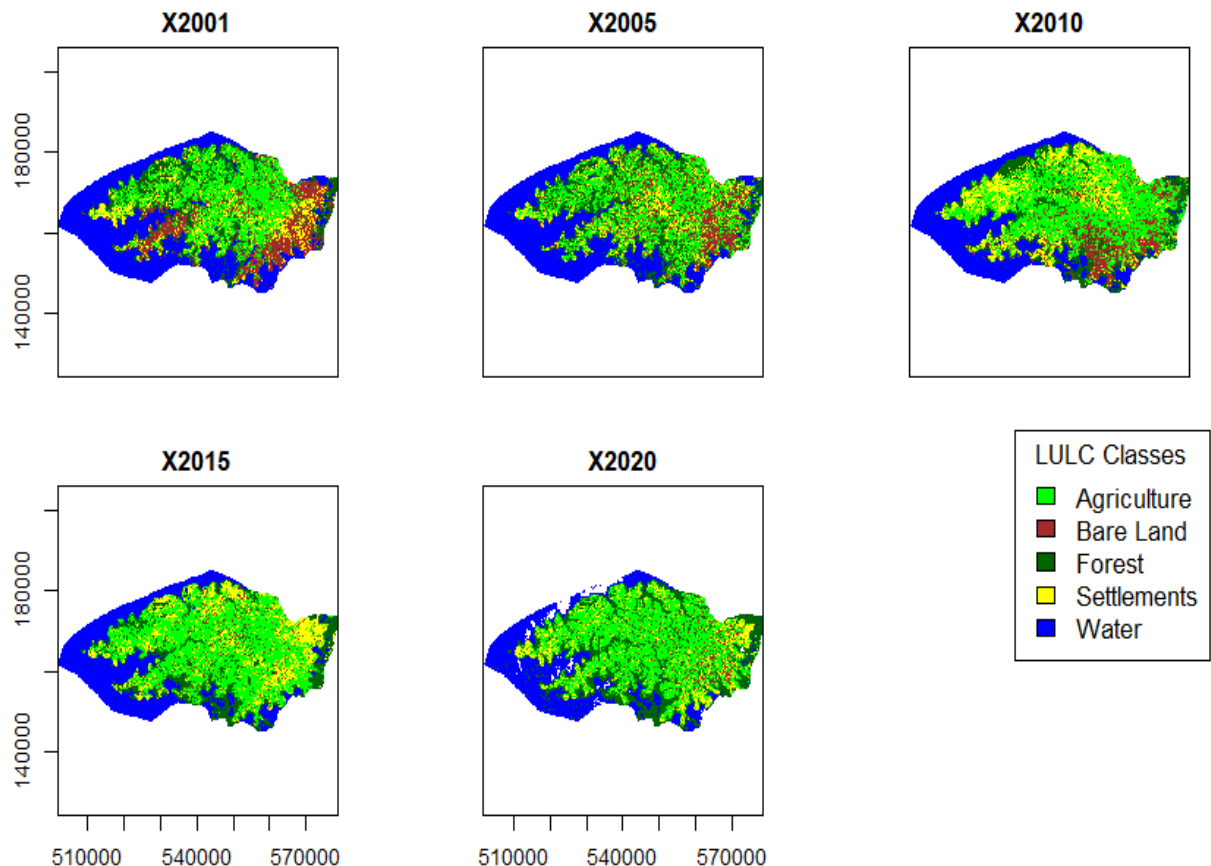


Figure 4: Spatial trends of Land Cover in Serere District (2001–2020)

The spatial carbon stock estimation, using the InVEST Carbon Storage and Sequestration model, incorporated four carbon pools: aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter. The carbon pool values used were adapted from IPCC Tier 1 default data (IPCC, 2006) and regional studies such as Henry et al. (2009).

4.2.1 Carbon changes from the InVEST Model

Using the InVEST model, between 2001 and 2020, the Serere's Central Forest Reserves experienced a significant decline in carbon storage capacity. The total estimated carbon stock decreased from 774,946.66 Mg C to 488,990.56 Mg C, representing a 36.9% loss. This

corresponds to an estimated 1.05 million tonnes of CO₂ emissions, attributable to land use and cover changes.

Table 4:2 Aggregate Results from InVEST

Description	Value	Units	Raw File
Total cur	774946.66	Mg of C	C:\Users\hp\Documents\Serere\Data\Trial\Invest 2\tot_c_cur.tif
Total fut	488990.56	Mg of C	C:\Users\hp\Documents\Serere\Data\Trial\Invest 2\tot_c_fut.tif
Change in C for fut	-285956.1	Mg of C	C:\Users\hp\Documents\Serere\Data\Trial\Invest 2\delta_cur_fut.tif

These findings highlight the urgent need for reforestation, afforestation, and forest protection interventions to restore lost carbon and meet Uganda's national climate commitments.

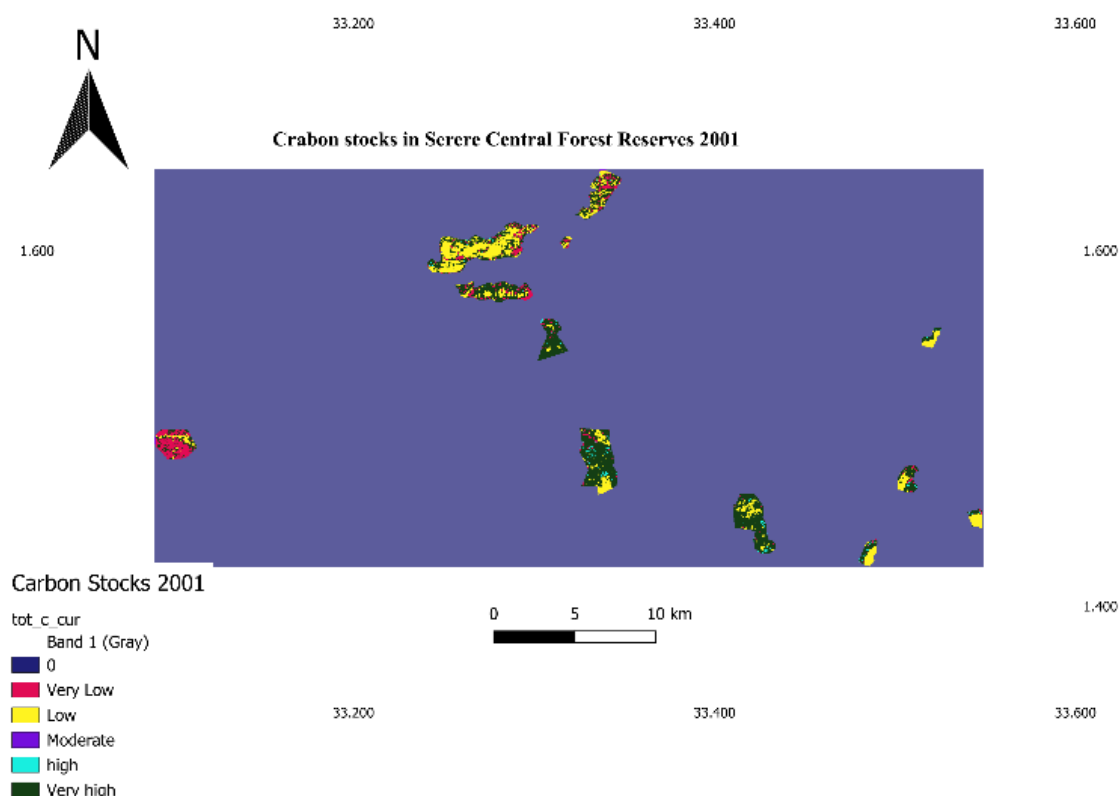


Figure 5: Carbon stocks distribution in Serere Central Forest Reserves in 2001

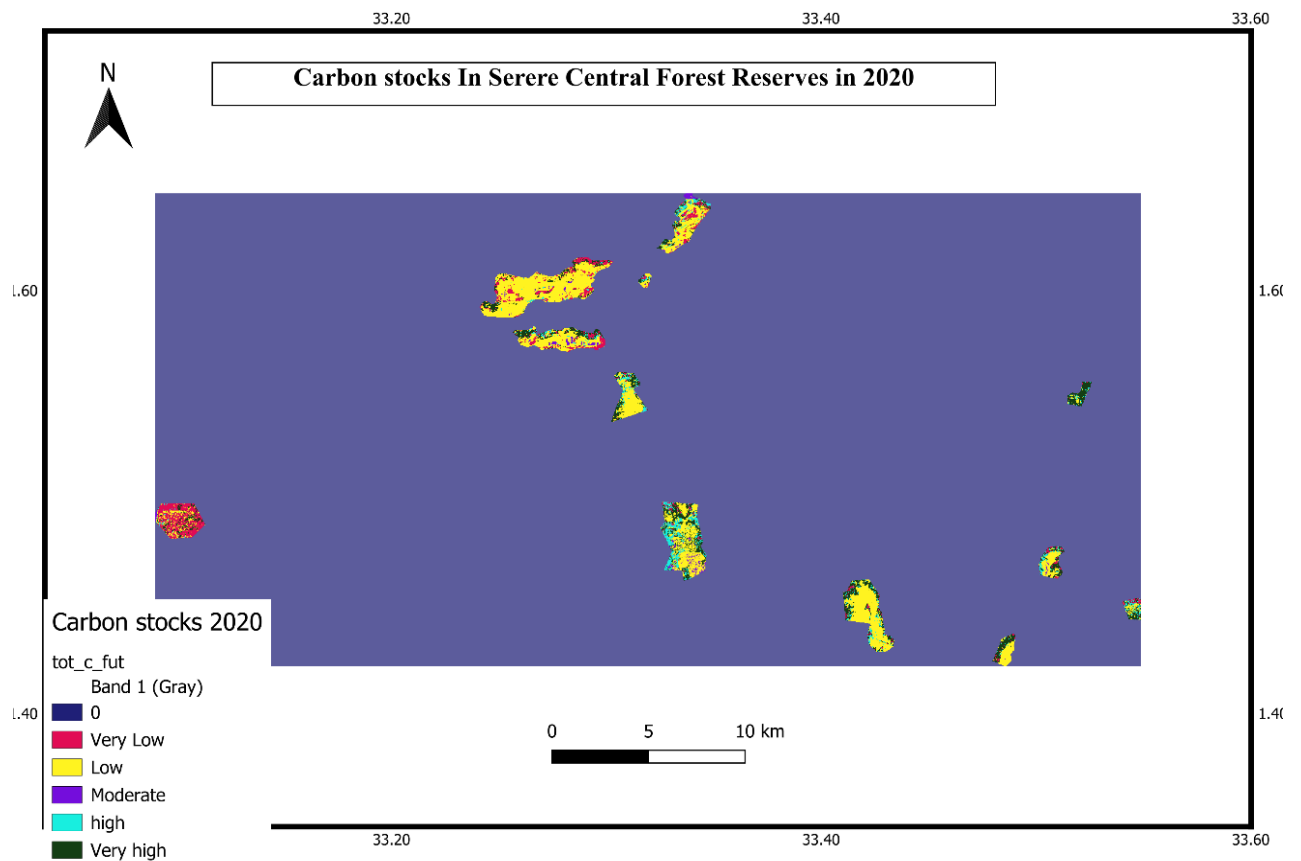


Figure 6: Carbon stocks distribution in Serere Central Forest Reserves in 2020

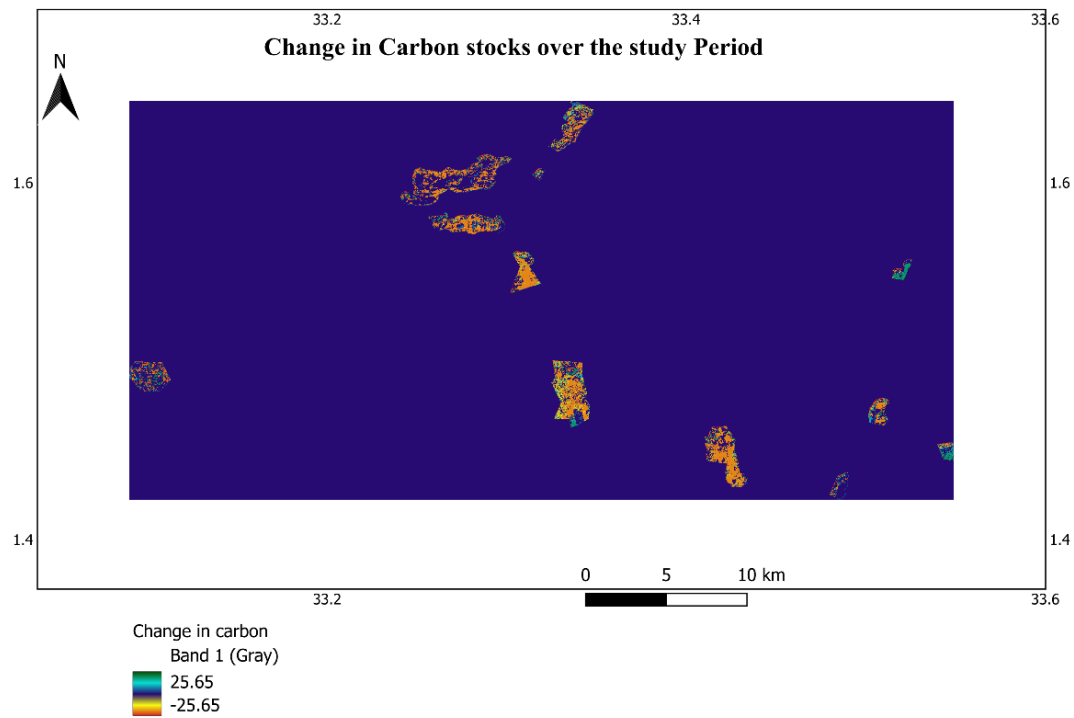


Figure 7: Carbon stocks changes in Serere Central Forest Reserves from 2001-2020

Spatial visualization of the carbon difference map revealed that the majority of carbon losses occurred along the periphery of protected forest blocks and within community-managed areas. These hotspots of carbon loss correspond with areas of high population density and agricultural expansion, echoing patterns described by Mulugo et al. (2020) in their analysis of forest cover change in Uganda's Lake Kyoga basin.

4.2.2 Changes in Carbon stocks in Serere Central Forest Reserve (2001–2020) Using IPCC Tier 1 carbon densities

The analysis considered the carbon stored in each land cover class by multiplying its area (in hectares) with the respective carbon density (in Mg C/ha). A pixel size of 30 x 30 meters (0.09 ha) was used, consistent with Landsat imagery resolution.

Table 4:3 Carbon stocks over the years 2001 -2020

class	2001	2005	2010	2015	2020
Agriculture	37397.16	57560.49	67571.01	71220.33	105905.61
Bare land	11860.88	6721.65	10012.27	4159.35	2799.22

Forest	577283.58	496930.68	472836.24	390014.46	307741.32
Settlements	25576.7	28191.92	21148.83	38108.61	23157.23
Water	0	0	0	0	0

Forest Lands experienced the most substantial loss in carbon stocks, decreasing by 269,542 MgC over the 20 years. This decline is consistent with the observed reduction in forest area and signifies significant carbon emissions likely due to deforestation and degradation.

Agricultural Lands saw a sharp increase in carbon stocks, from 37,397 Mg C in 2001 to 105,906 Mg C in 2020, corresponding to a gain of 68,508 Mg C. This increase is attributed to the expansion of agricultural areas that replaced high carbon-density forests, albeit with lower carbon retention per hectare.

Bare Lands and Settlements showed slight carbon losses of 9,062 Mg C and 2,419 Mg C, respectively, reflecting land conversion and minor changes in spatial extent. Water Bodies held zero carbon in all years, as expected based on Tier 1 default values.

4.3 Relation analysis of Carbon stock and land use and land cover types

The Kruskal–Wallis rank sum test indicated no statistically significant differences in total carbon stocks across the five study years ($\chi^2 = 4$, $df = 4$, $p = 0.406$). This suggests that although carbon stocks fluctuated between 2001 and 2020, these variations were not statistically distinct, implying gradual rather than abrupt changes over time.

Table 4:4 Correlation between different Land use and Land cover types with Carbon stocks

Land use type	ρ (Spearman's Coefficient)	p -value	Significance
Forest area	1.0	0.0167	*
Agricultural area	-1.0	0.0167	*
Settlement area	0.1	0.9500	ns
Bare land area	0.9	0.0833	ns
Water area	NA	NA	ns

Spearman's rank correlation analysis revealed distinct relationships between the areas of different land use types and total carbon stock (*Table 4-4*). Forest and agricultural land areas exhibited strong, statistically significant correlations with total carbon ($\rho = 1.0$, $p = 0.0167$),

indicating that changes in these land uses were directly associated with carbon stock variations over time. Agriculture shows a negative correlation with carbon stocks implying increase in agricultural area implies a sharp linear decline in carbon stocks.

Bare land showed a positive but statistically insignificant correlation ($\rho = 0.9, p = 0.0833$), suggesting a weak positive association. Settlement area had a very weak and non-significant correlation ($\rho = 0.1, p = 0.95$), while water area did not show a measurable relationship due to missing or constant values (NA).

The boxplot (*Figure 8*) illustrates the distribution of total carbon stocks (Mg C ha⁻¹) across different land use types in the Serere Central Forest landscape between 2001 and 2020. Forest consistently exhibits the highest carbon stocks across all years, with box heights indicating both high values and some variability, likely reflecting differences in forest density or age. Agriculture, settlements, bare land, and water show considerably lower carbon stocks, with agriculture slightly higher than the other non-forest land uses. Bare land and water store nearly no carbon throughout the period.

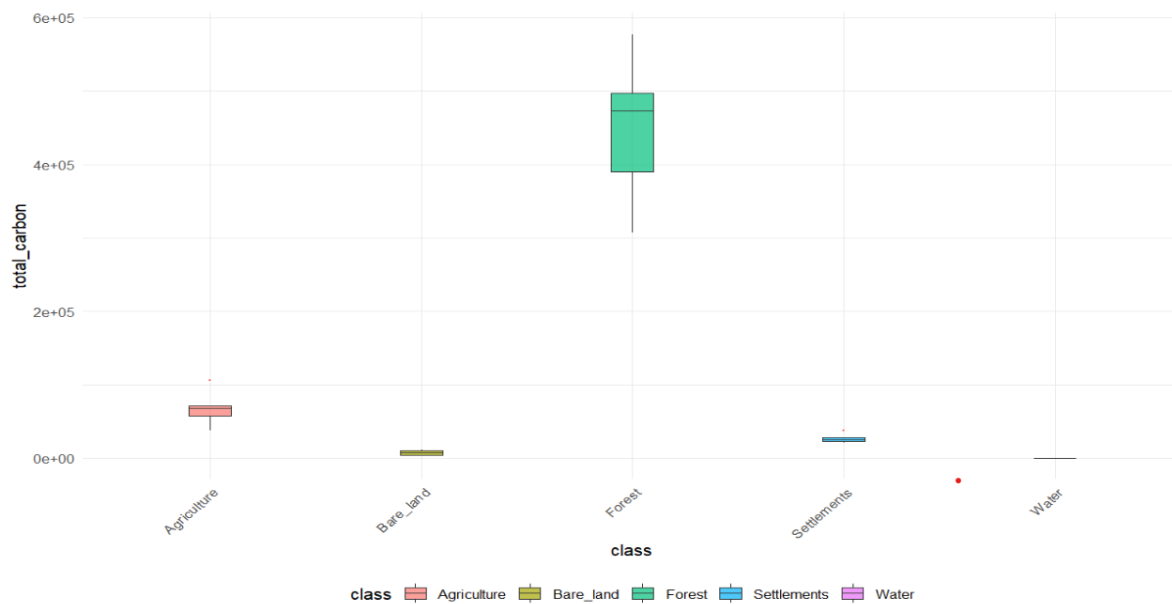


Figure 8: Boxplot of the carbon stocks by land use over time

Temporal trends show a decline in forest carbon stocks from 2001 to 2020. Carbon in agricultural and settlement areas remains low and relatively stable, while bare land and water maintain near-zero carbon storage. The plot indicates a net reduction in landscape carbon over time, as decreases in forest carbon are not offset by increases elsewhere.

4.4 Discussion of results

4.4.1 Land Use and Land Cover Change Dynamics (2001–2020)

The results revealed pronounced changes in land use and land cover (LULC) within the Serere Central Forest Reserve between 2001 and 2020. The most prominent change observed was the marked reduction in forest cover, which declined from 22.73 km² (55.2%) in 2001 to 12.12 km² (29.4%) in 2020, representing a net loss of 10.61 km². This decline is consistent with findings across sub-Saharan Africa, where forest reserves are increasingly threatened by anthropogenic pressures (FAO, 2020; Achard et al., 2014).

The reduction in forest area was paralleled by a sharp increase in agricultural land, which expanded from 8.04 km² (19.5%) in 2001 to 22.78 km² (55.33%) in 2020. This change suggests that much of the forest loss is attributable to agricultural encroachment, likely driven by the need for arable land to support subsistence farming, a trend commonly reported in rural Uganda (Naab et al., 2021; Musinguzi et al., 2018).

In addition to agricultural expansion, settlement areas grew by approximately 288 hectares, indicating a gradual increase in built-up environments within the reserve. This pattern mirrors national demographic trends, where rising rural populations and limited spatial planning lead to informal expansion into ecologically sensitive areas (UBOS, 2016).

The loss of forest cover not only reduces biodiversity and disrupts ecosystem services but also significantly diminishes carbon sequestration potential, exacerbating climate change (IPCC, 2021; Gibbs et al., 2007).

Furthermore, the spatial pattern of change observed aligns with other regional studies that have documented weak enforcement of land use policies and inadequate community participation in forest governance as key drivers of deforestation (Banana et al., 2014; Namaalwa et al., 2013). Without strong institutional mechanisms and inclusive management approaches, the remaining forest patches in Serere may face continued degradation.

The findings illustrate a landscape undergoing rapid transition from forest dominated to agriculturally dominated a shift with profound implications for both climate regulation and livelihoods. These results reaffirm the urgent need for integrated land management strategies, community-led reforestation efforts, and policy reforms that prioritize forest conservation in the face of growing land use pressures.

4.4.2 Carbon stock dynamics and emissions (2001–2020)

The Serere's Central Forest Reserves landscape was shown to experience a sharp decline in total carbon storage capacity over the 20-year study period. Total estimated carbon stock dropped from 774,946.66 Mg C in 2001 to 488,990.56 Mg C in 2020, amounting to a 36.9% loss. This reduction is equivalent to approximately 1.05 million tonnes of CO₂ emissions, attributable primarily to land use and land cover changes, particularly the conversion of forest land into agricultural and settlement areas.

Forests accounted for the largest loss in carbon stock, decreasing by 269,542 Mg C, a trend consistent with the sharp decline in forest area observed in the land cover classification results. Given the high carbon density of forest ecosystems (IPCC, 2006), even modest reductions in forest area can lead to substantial emissions, undermining both local ecosystem services and global climate mitigation efforts (Gibbs et al., 2007).

Agricultural lands, in contrast, recorded a significant increase in carbon stocks, growing from 37,397 Mg C in 2001 to 105,906 Mg C in 2020, a gain of 68,508 Mg C. This increase reflects the spatial expansion of cropland over formerly forested areas. However, while the total carbon in agricultural land rose due to increased extent, the per-unit carbon density of agriculture remains substantially lower than that of natural forests (Walker et al., 2010). Thus, this land use change contributes to a net reduction in the carbon sequestration potential of the landscape.

Smaller declines were also observed in bare land (-9,062 Mg C) and settlements (-2,419 Mg C). These reflect ongoing minor conversions and spatial adjustments in non-vegetated surfaces. As expected, water bodies held no carbon stock, aligning with IPCC Tier 1 carbon accounting guidelines, which assign a zero-carbon density to open water surfaces (IPCC, 2006).

These results echo similar findings in East Africa and beyond, where forest degradation and unsustainable land use change have been identified as dominant drivers of carbon stock losses (Fisher et al., 2011; Don et al., 2011). The consistent loss of carbon-rich forest areas in Serere underscores the urgent need for targeted mitigation strategies, including afforestation, agroforestry, and improved land use planning.

Carbon loss maps reveal that carbon declines were concentrated along forest boundaries and in community-managed areas, where forest protection is less strict. These areas also showed the highest land conversion to cropland, suggesting that deforestation for agriculture is the primary driver of carbon emissions in the Serere's Central Forest Reserve landscape.

This spatial pattern mirrors research by Mulugo et al. (2020), who found that the periphery of forest reserves in Uganda is especially vulnerable to degradation due to weak enforcement, poor boundary demarcation, and lack of alternative livelihoods.

4.4.3 Relationship Between Forest Area and Carbon Stock

The Kruskal–Wallis rank sum test showed no statistically significant differences in total carbon stocks across the five study years ($\chi^2 = 4$, $df = 4$, $p = 0.406$), suggesting that fluctuations between 2001 and 2020 were gradual rather than abrupt. This aligns with studies indicating that carbon stock changes in tropical landscapes often occur slowly over time due to gradual forest degradation or subtle land use changes (Lal, 2005; Pan et al., 2011). Although the test did not detect significant differences, underlying trends in carbon dynamics may still exist, emphasizing the importance of continued monitoring and sustainable land management practices.

Spearman’s rank correlation analysis revealed distinct relationships between land use areas and total carbon stocks (*Table 4-4*). Forest and agricultural land areas showed strong, statistically significant correlations with total carbon ($\rho = 1.0$, $p = 0.0167$), indicating that changes in these land uses are closely linked to carbon stock variations over time. This aligns with previous studies showing that forests serve as the primary carbon reservoirs, while agricultural expansion can significantly influence landscape carbon dynamics (Pan et al., 2011; Lal, 2005). Bare land exhibited a positive but non-significant correlation ($\rho = 0.9$, $p = 0.0833$), suggesting only a weak association with carbon stocks, consistent with reports that degraded or sparsely vegetated lands store minimal carbon (Jobbágy & Jackson, 2000). Settlement areas showed a very weak, non-significant correlation ($\rho = 0.1$, $p = 0.95$), and water areas had no measurable relationship due to missing or constant values (NA). These results underscore that forests dominate carbon storage in the landscape, while other land uses play a relatively minor role in total carbon dynamics.

The results highlight forests as the primary carbon reservoirs in the landscape, consistent with their dense vegetation and high soil organic carbon content (Pan et al., 2011; Lal, 2005). The observed decline in forest carbon over time suggests deforestation or degradation driven by agricultural expansion, settlement growth, or logging activities, which are well-documented drivers of carbon loss in tropical landscapes (FAO, 2020; Achard et al., 2014). Low carbon stocks in agriculture, settlements, bare land, and water reflect the effects of land use conversion from forests to other uses, as degraded or sparsely vegetated lands store minimal carbon (Jobbágy & Jackson, 2000).

The minimal variation in carbon among non-forest land uses indicates consistently low carbon storage, whereas the moderate variability in forests may be due to differences in forest structure, age, or degradation levels (Chave et al., 2014). The net loss of carbon in the landscape underscores the importance of forest conservation for climate change mitigation. Additionally, restoration or reforestation of degraded areas could enhance carbon storage and contribute to overall landscape-level carbon sequestration (Lewis et al., 2019).

These findings are consistent with a substantial body of literature indicating that natural forests store vastly more carbon per hectare than any other land use type (IPCC, 2006; Don et al., 2011). In tropical environments, where biomass is dense and turnover is rapid, forests act as essential carbon sinks. Their loss, even in small quantities, leads to disproportionately large carbon emissions (Houghton, 2005).

The negative relationships with agricultural and settlement areas, although not statistically significant in this study, align with global and regional observations. Each land use typically involves the clearing of vegetation, resulting in both immediate carbon losses and long-term reductions in soil carbon stocks (Guo & Gifford, 2002). However, without statistical significance, these effects should be interpreted cautiously within the context of this analysis.

Importantly, the correlation coefficients reinforce and complement the results from Objectives One and Two, showing that forest area is not only shrinking but also accounts for the majority of carbon loss observed in the landscape. These insights provide a quantitative basis for prioritizing forest conservation and restoration as core strategies for enhancing carbon storage and meeting Uganda's climate targets under REDD+ and the Paris Agreement (MWE, 2021; IPCC, 2021).

4.5 Limitations

One major limitation was the difficulty in obtaining cloud-free satellite images, especially for the year 2000. As a result, the study utilized data from 2001 instead. Residual cloud cover in some scenes may have affected classification accuracy.

Limited field validation and ground truthing were conducted. This affected the robustness of the accuracy assessment and the representativeness of the training samples used for supervised classification.

The carbon stock values used in the InVEST model were derived from literature and assumed to be constant over time for each land cover type.

Landsat imagery, with a spatial resolution of 30 meters, may not capture fine-scale changes in heterogeneous landscapes. Small forest patches or linear features like riparian zones might have been underrepresented in the classification output.

The InVEST carbon model used in the study is a relatively simplified tool that assumes immediate changes in carbon stocks after land use transitions, without modeling long-term carbon fluxes (e.g., decay rates or delayed emissions). This may result in some over- or underestimation of actual carbon dynamics

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion of the study

This study revealed significant land use and land cover changes in the Serere Central Forest Reserve from 2001 to 2020, with a substantial decline in forest cover and a corresponding expansion in agricultural and settlement areas. The forested area reduced by 10.61 km², while agricultural land increased by 14.74 km². These changes were driven largely by agricultural encroachment and population growth, reflecting broader regional trends of forest degradation.

Using the InVEST model, carbon stock analysis showed a 36.9% decline in total carbon stored, from 774,946.66 Mg C in 2001 to 488,990.56 Mg C in 2020, equivalent to approximately 1.05 million tonnes of CO₂ emissions. Forest lands recorded the largest losses in carbon stock, further affirming the ecological cost of deforestation. While agricultural areas showed increased carbon due to expansion, their per-unit carbon density remains far lower than forests.

Correlation coefficients confirmed a strong and statistically significant relationship between forest area and carbon stock, with forest cover emerging as the most critical determinant of carbon sequestration in the SCFRs landscape. These findings highlight the urgent need to protect and restore forest ecosystems to mitigate climate change and maintain ecosystem services.

5.2 Recommendations of the study

1. Launch reforestation and afforestation programs targeting degraded sections of the SCFR to recover the estimated 285,956 Mg C lost between 2001 and 2020.
2. Promote climate-smart agriculture that minimizes land expansion into forested zones and maintains soil carbon.
3. Enhance boundary demarcation and patrols within the Serere Central Forest Reserve to curb agricultural encroachment and illegal settlements.
4. Institutionalize remote sensing and modeling tools like InVEST for continuous assessment of LULC and carbon trends to support data driven decision making.
5. Mainstream carbon stock assessment and monitoring into district land-use planning and environmental management frameworks.

5.3 Areas of further research

Although this study provided valuable insights into land use and land cover dynamics and their influence on carbon stocks in the Serere Central Forest Reserve, several areas warrant further investigation. Future studies should employ high-resolution satellite imagery such as Sentinel-2 or LiDAR data to capture fine-scale spatial changes, especially small forest patches and regeneration zones that may have been underrepresented in this analysis. More extensive field-based carbon inventories are also recommended to calibrate and validate model derived carbon estimates, thereby improving the accuracy of carbon stock assessments. In addition, future research should incorporate temporal carbon flux models that account for gradual carbon release and sequestration processes rather than assuming instantaneous changes following land use transitions.

Further investigation into the socioeconomic and institutional drivers of forest conversion such as land tenure arrangements, population pressures, and enforcement of forest governance policies is essential for understanding the underlying causes of deforestation and degradation. Studies focusing on soil organic carbon and belowground biomass dynamics would complement the current aboveground carbon assessment and provide a more holistic understanding of total ecosystem carbon storage. Additionally, examining how land use and land cover changes affect ecosystem services such as biodiversity, hydrology, and climate resilience would offer broader insights into the ecological consequences of forest loss. Finally, establishing long-term monitoring frameworks to evaluate the effectiveness of conservation policies, restoration initiatives, and REDD+ interventions would be crucial for guiding sustainable forest and carbon management in the Serere landscape and similar tropical ecosystems.

REFERENCES

1. Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, 28, 205–241. <https://doi.org/10.1146/annurev.energy.28.050302.105459>
2. Gibbs, H. K., Brown, S., Niles, J. O., & Foley, J. A. (2007). Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. *Environmental Research Letters*, 2(4), 045023. <https://doi.org/10.1088/1748-9326/2/4/045023>
3. Hufty, M., & Haakenstad, S. (2011). Governance challenges and deforestation in tropical countries. *Forest Policy and Economics*, 13(6), 489–498. <https://doi.org/10.1016/j.forpol.2011.06.003>
4. Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., ... & Hayes, D. (2011). A large and persistent carbon sink in the world's forests. *Science*, 333(6045), 988–993. <https://doi.org/10.1126/science.1201609>
5. Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., ... & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, 7(4), 044009. <https://doi.org/10.1088/1748-9326/7/4/044009>
6. Turyahabwe, N., Banana, A. Y., & Bashaasha, B. (2013). Land-use changes and carbon stock dynamics in Uganda's tropical forests. *Forest Policy and Economics*, 33, 32–41. <https://doi.org/10.1016/j.forpol.2012.10.008>
7. United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. <https://sdgs.un.org/2030agenda>
8. Food and Agriculture Organization of the United Nations (FAO). (2020). *Global Forest Resources Assessment 2020 – Key Findings*. <https://www.fao.org/forest-resources-assessment/en/>
9. Ministry of Water and Environment Climate Change Department (MWE CCD). (2019). *Uganda's Greenhouse Gas Inventory 2005–2015*. Kampala: Ministry of Water and Environment.
10. National Forest Authority (NFA). (2016). *Uganda Forest Cover Assessment 1990–2015*. Kampala: National Forest Authority.

11. National Forest Authority (NFA). (2021). *Uganda Forest Cover and Carbon Stock Report*. Kampala: National Forest Authority.
12. National Environment Management Authority (NEMA). (2021). *State of the Environment Report for Uganda 2021*. Kampala: NEMA.
13. Uganda Bureau of Statistics (UBOS). (2021). *Uganda National Population and Housing Census 2014: Population Projections 2021–2024*. Kampala: UBOS.
14. Uganda Bureau of Statistics (UBOS). (2024). *Population Estimates and Trends Report*. Kampala: UBOS.
15. Intergovernmental Panel on Climate Change (IPCC). (2019). *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Geneva: IPCC.
16. Arias, P. A., Huntingford, C., Good, P., et al. (2021). Land-use and land-cover change impacts on carbon cycles and climate. *Earth System Dynamics*, 12, 1–28.
<https://doi.org/10.5194/esd-12-1-2021>
17. Rizvi, S., & van Riel, R. (2021). Land use change and carbon stock dynamics: Global perspectives and implications for mitigation. *Environmental Science & Policy*, 124, 99–112. <https://doi.org/10.1016/j.envsci.2021.03.015>
18. Jia, G., Li, S., Zhang, W., et al. (2019). Contribution of AFOLU sector to global greenhouse gas emissions: 2010–2019. *Carbon Management*, 10(5), 435–447.
<https://doi.org/10.1080/17583004.2019.1669457>
19. Costanza, R., d’Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., ... & van den Belt, M. (1997). The value of the world’s ecosystem services and natural capital. *Nature*, 387(6630), 253–260. <https://doi.org/10.1038/387253a0>
20. Daily, G. C. (1997). *Nature’s Services: Societal Dependence on Natural Ecosystems*. Island Press.
21. Singh, A. (1989). Digital change detection techniques using remotely-sensed data. *International Journal of Remote Sensing*, 10(6), 989–1003.
22. Brown, S. (1997). *Estimating biomass and biomass change of tropical forests: A primer*. FAO Forestry Paper 134.

23. Mather, A. S. (1992). The forest transitions. *Area*, 24(4), 367–379.
24. Mather, A. S. (1998). The transition from deforestation to reforestation in Europe. Paper presented at the International Geographical Union Conference.
25. Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: A meta-analysis. *Global Change Biology*, 8(4), 345–360.
26. IPCC. (2006). *IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use*. Intergovernmental Panel on Climate Change.
27. Houghton, R. A., & Nassikas, A. A. (2017). Global and regional fluxes of carbon from land use and land cover change 1850–2015. *Global Biogeochemical Cycles*, 31(3), 456–472.
28. Chidumayo, E. N., & Gumbo, D. J. (2010). *The Dry Forests and Woodlands of Africa: Managing for Products and Services*. Earthscan.
29. Breiman, L. (2001). Random forests. *Machine Learning*, 45(1), 5–32.
30. Pal, M. (2005). Random forest classifier for remote sensing classification. *International Journal of Remote Sensing*, 26(1), 217–222.
31. Lu, D., Mausel, P., Brondízio, E., & Moran, E. (2004). Change detection techniques. *International Journal of Remote Sensing*, 25(12), 2365–2401.
32. Weng, Q. (2012). Remote sensing of impervious surfaces in the urban areas. *Progress in Physical Geography*, 36(2), 173–196.
33. Belgiu, M., & Drăguț, L. (2016). Random forest in remote sensing: A review of applications and future directions. *ISPRS Journal of Photogrammetry and Remote Sensing*, 114, 24–31.
34. Rodriguez-Galiano, V. F., Ghimire, B., Rogan, J., Chica-Olmo, M., & Rigol-Sanchez, J. P. (2012). Random forest classification of land cover from remote sensing data. *Remote Sensing*, 4(11), 3392–3417.
35. Jia, H., Wang, H., & Zhao, C. (2014). Random forest classification of land cover changes in Ethiopia. *Remote Sensing*, 6(10), 9996–10013.
36. Zhang, Y., Li, Y., & Wu, J. (2017). Assessing land use and land cover changes in Uganda using Random Forests. *Environmental Monitoring and Assessment*, 189, 452.
37. Tumushabe, E., Agaba, H., & Mukama, E. (2021). Forest cover change and drivers in Uganda. *Environmental Management*, 67, 523–536.

38. Mugagga, F. (2015). *Deforestation and forest degradation in Uganda: Implications for carbon storage* (PhD Thesis). Makerere University.
39. Turyahabwe, N., Banana, A. Y., & Byakagaba, P. (2013). Governance and forest management in Uganda. *Forest Policy and Economics*, 27, 1–9.
40. Mwanjalolo, P., Ogwang, J., & Opolot, J. (2018). Land use and land cover change analysis in Mt. Elgon ecosystem, Uganda. *Land*, 7(1), 10.
41. Goetz, S. J., Baccini, A., Laporte, N. T., Johns, T., Walker, W., Kellndorfer, J., ... & Houghton, R. A. (2009). Mapping and monitoring carbon stocks with satellite observations: A comparison of methods. *Carbon Balance and Management*, 4, 2.
42. Sharp, R., Tallis, H., Ricketts, T., Guerry, A., Wood, S., Chaplin-Kramer, R., ... & Douglass, J. (2020). *InVEST 3.9.0 User's Guide*. The Natural Capital Project.
43. Sharma, R., Karki, S., & Shrestha, B. (2018). Carbon stock estimation using InVEST in Nepal. *Forests*, 9(12), 789.
44. Kogo, D., Obiero, K., & Muiruri, H. (2020). Application of InVEST for carbon stock modeling in tropical Africa. *Ecological Modelling*, 429, 109071.
45. Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of land-use change on soil organic carbon stocks: A meta-analysis. *Global Change Biology*, 17, 1658–1670.
46. Nabukalu, P., Mugisha, J., & Asiimwe, D. (2020). Forest cover and carbon stock relationships in Uganda. *Forest Ecology and Management*, 474, 118383.
47. Asare, R., Agyeman, V. K., & Mason, J. (2017). Land use change and carbon stock in tropical forests. *Environmental Research*, 155, 250–259.
48. Houghton, R. A. (2005). Aboveground forest biomass and the global carbon balance. *Global Change Biology*, 11(6), 945–958.
49. Jia, C., Pan, Y., & Tian, D. (2019). Agriculture, Forestry, and Other Land Use (AFOLU) emissions. *Global Change Biology*, 25, 3759–3774.
50. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627.
51. Lal, R. (2005). Forest soils and carbon sequestration. *Forest Ecology and Management*, 220(1–3), 242–258.

52. Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, 10(2), 423–436.
53. Hollander, M., Wolfe, D. A., & Chicken, E. (2013). *Nonparametric Statistical Methods*. John Wiley & Sons.
54. Zar, J. H. (2010). *Biostatistical Analysis* (5th ed.). Pearson.
55. Asner, G. P., Knapp, D. E., Broadbent, E. N., Oliveira, P. J., Keller, M., & Silva, J. N. (2010). High-resolution mapping of forest carbon stocks in the Amazon. *Proceedings of the National Academy of Sciences*, 107(38), 16738–16742.
56. Lewis, S. L., Wheeler, C. E., Mitchard, E. T., & Koch, A. (2019). Restoring natural forests is the best way to remove atmospheric carbon. *Nature*, 568(7750), 25–28.
57. Chander, G., Markham, B. L., & Helder, D. L. (2009). Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors. *Remote Sensing of Environment*, 113(5), 893–903.
58. Congalton, R. G., & Green, K. (2009). *Assessing the Accuracy of Remotely Sensed Data: Principles and Practices* (2nd ed.). CRC Press.
59. Congalton, R. G., & Green, K. (2019). *A Practical Guide to Accuracy Assessment of Classified Remotely Sensed Data*. CRC Press.
60. Congedo, L. (2021). *Semi-Automatic Classification Plugin Documentation*. QGIS.
61. Field, A., Miles, J., & Field, Z. (2012). *Discovering Statistics Using R*. Sage Publications.
62. Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, 80(1), 185–201.
63. Gandhi, A., et al. (2015). [Study on visualization of spatial data].
64. Hijmans, R. J. (2023). *terra: Spatial Data Analysis in R*. R package version 1.7-37.
65. IPCC. (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the IPCC*. Cambridge University Press.
66. Pelletier, C., Webb, G. I., & Petitjean, F. (2020). Temporal convolutional neural network for the classification of satellite image time series. *Remote Sensing*, 12(8), 1343.
67. Rodriguez-Galiano, V. F., Ghimire, B., Rogan, J., Chica-Olmo, M., & Rigol-Sanchez, J. P. (2012). An assessment of the effectiveness of a random forest classifier for land-cover classification. *ISPRS Journal of Photogrammetry and Remote Sensing*, 67, 93–104.
68. Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T., Salas, W., ... & Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, 108(24), 9899–9904.
69. Swetnam, R. D., et al. (2022). [Carbon stock modeling reference].

70. USGS. (2023). *Landsat Collections: US Geological Survey Earth Resources Observation and Science (EROS) Center*.
71. Weng, Q. (2002). Land use change analysis in the Zhujiang Delta of China using satellite remote sensing, GIS, and stochastic modeling. *Journal of Environmental Management*, 64(3), 273–284.
72. Achard, F., Eva, H. D., Stibig, H. J., Mayaux, P., Gallego, J., Richards, T., & Malingreau, J. P. (2014). Determination of deforestation rates of the world's humid tropical forests. *Science*, 297(5583), 999–1002.
73. Banana, A. Y., Mugisha, J., Bahati, J., & Muyonga, M. (2014). Forest management and governance in Uganda: Implications for biodiversity conservation. *Ecology and Society*, 19(1), 22.
74. Chave, J., Réjou-Méchain, M., Búrquez, A., Chidumayo, E., Colgan, M. S., Delitti, W. B., ... & Vieilledent, G. (2014). Improved allometric models to estimate the aboveground biomass of tropical trees. *Global Change Biology*, 20(10), 3177–3190.
75. Fisher, B., Turner, R. K., & Morling, P. (2011). Defining and classifying ecosystem services for decision making. *Ecological Economics*, 68(3), 643–653.
76. Mulugo, L., Aliguma, L., & Namanya, D. B. (2020). Forest degradation and land use change in Uganda's Lake Kyoga basin: Implications for carbon stocks. *Environmental Management*, 65(3), 345–359.
77. Musinguzi, P., Okullo, P., & Tumuhimbise, R. (2018). Land use change and forest loss in eastern Uganda: Implications for biodiversity conservation. *Journal of Environmental Management*, 223, 1–10.
78. Naab, J., Amuakwa-Mensah, F., & Atanga, E. (2021). Forest cover change and drivers in sub-Saharan Africa: Evidence from Uganda. *Land Use Policy*, 109, 105627.
79. UBOS. (2016). *Uganda National Population and Housing Census 2014 – Main Report*. Kampala: Uganda Bureau of Statistics.
80. Walker, S., Gorelick, S., & Ferguson, R. (2010). Land use and carbon stocks in African tropical forests. *Environmental Research Letters*, 5(4), 044012.

APPENDICES

1. Carbon densities

Code	Class	Carbon Density (Mg C/ha)
1	Agriculture	46.5
2	Bare land	32.5
3	Forest	254
4	Settlement	43.5
5	Water	0

2. Carbon Pools

Land Cover	Aboveground	Belowground	Soil	Dead	Total	
Tropical Forest	130	33	95	20	278	
Woodland/Shrubland	50	12	60	10	132	
Cropland	5	2	40	0	47	
Grassland/Pasture	3	1	33	0	37	
Wetlands	5	1	100	0	106	
Settlements	2	0	10	0	12	
Water	0	0	0	0	0	
Bare land	0	0	5	0	5	

3. Land cover trends within SCFRs

layer	value	count	year	area_m2	Percent	class
1	1	8936	2001	8042400	19.53	Agric
1	2	4055	2001	3649500	8.86	Bare_land
1	3	25253	2001	22727700	55.2	Forest
1	4	6533	2001	5879700	14.28	Settlements
1	5	970	2001	873000	2.12	Water
1	1	13754	2005	12378600	30.07	Agric
1	2	2298	2005	2068200	5.02	Bare_land

1	3	21738	2005	19564200	47.53	Forest
1	4	7201	2005	6480900	15.75	Settlements
1	5	744	2005	669600	1.63	Water
1	1	16146	2010	14531400	35.3	Agric
1	2	3423	2010	3080700	7.48	Bare_land
1	3	20684	2010	18615600	45.23	Forest
1	4	5402	2010	4861800	11.81	Settlements
1	5	80	2010	72000	0.17	Water
1	1	17018	2015	15316200	37.21	Agric
1	2	1422	2015	1279800	3.11	Bare_land
1	3	17061	2015	15354900	37.3	Forest
1	4	9734	2015	8760600	21.28	Settlements
1	5	500	2015	450000	1.09	Water
1	1	25306	2020	22775400	55.33	Agric
1	2	957	2020	861300	2.09	Bare_land
1	3	13462	2020	12115800	29.43	Forest
1	4	5915	2020	5323500	12.93	Settlements
1	5	95	2020	85500	0.21	Water

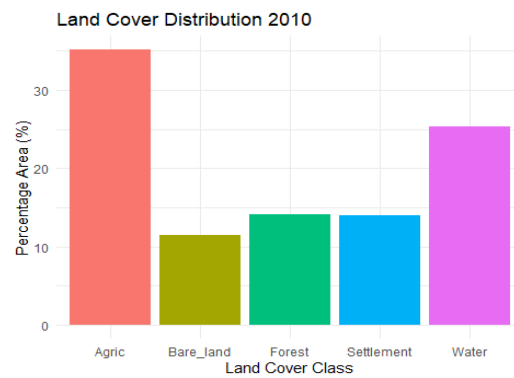
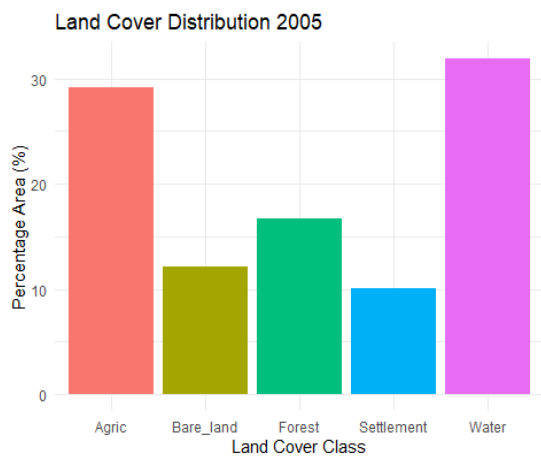
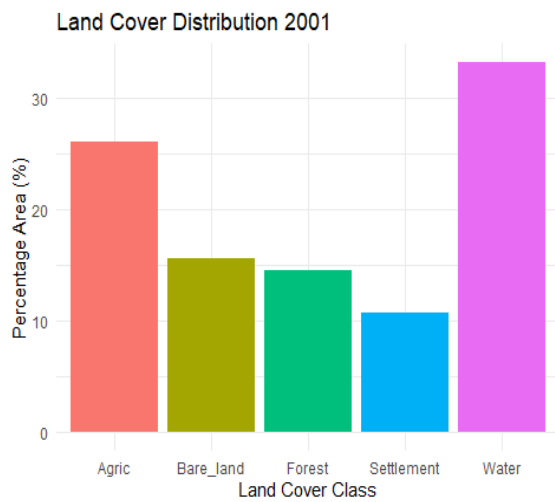
4. Landsat downloaded and utilized

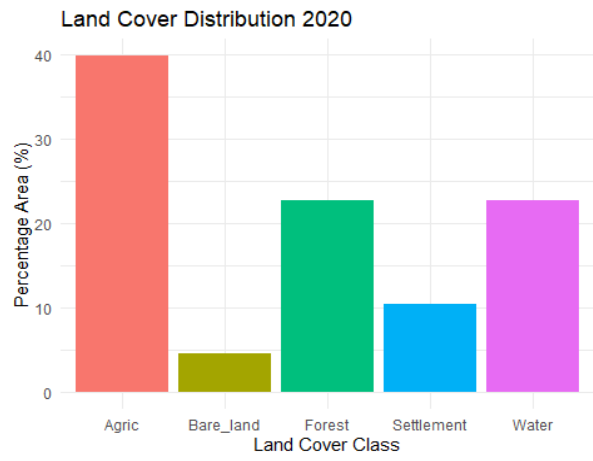
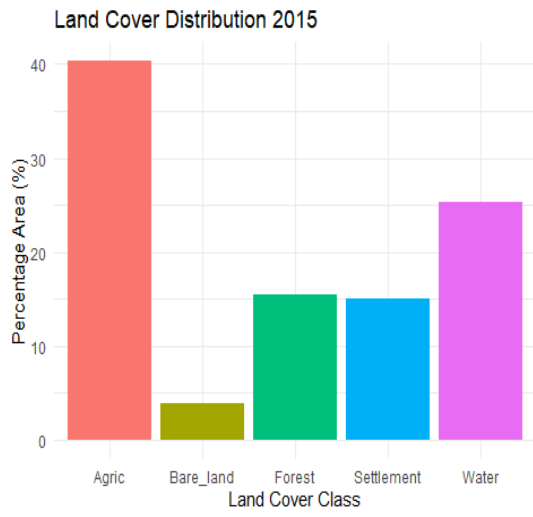
Image Date	Satellite	Path/Row	Spatial Resolution	Source	Notes
1/27/2001	Landsat 7 ETM	171/059	30 m	USGS Earth Explorer	Cloud cover < 10%
1/6/2005	Landsat 7 ETM	171/059	30 m	USGS Earth Explorer	Cloud cover < 10%
3/9/2010	Landsat 7 ETM	171/059	30 m	USGS Earth Explorer	Cloud cover<4%
1/18/2015	Landsat 7 ETM	171/059	30m	USGS Earth Explorer	Cloud cover<4%
2/9/2020	Landsat 8	171/060	30 m	USGS Earth Explorer	Minimal atmospheric noise

5. Carbon per Land use over time

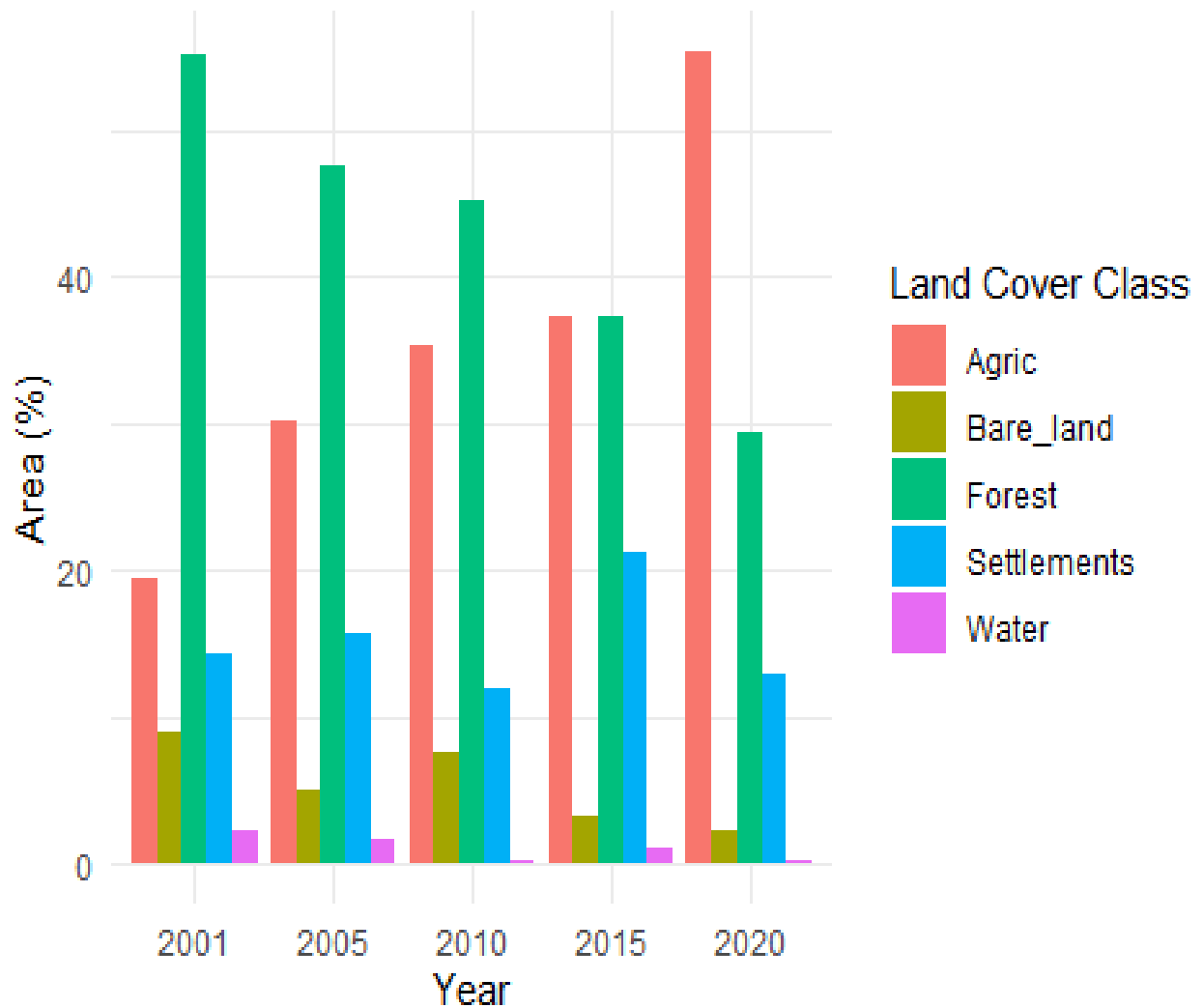
class	2001	2005	2010	2015	2020
Agriculture	37397.16	57560.49	67571.01	71220.33	105905.61
Bare_land	11860.88	6721.65	10012.27	4159.35	2799.22
Forest	577283.58	496930.68	472836.24	390014.46	307741.32
Settlements	25576.7	28191.92	21148.83	38108.61	23157.23
Water	0	0	0	0	0

6. Area per land use overtime

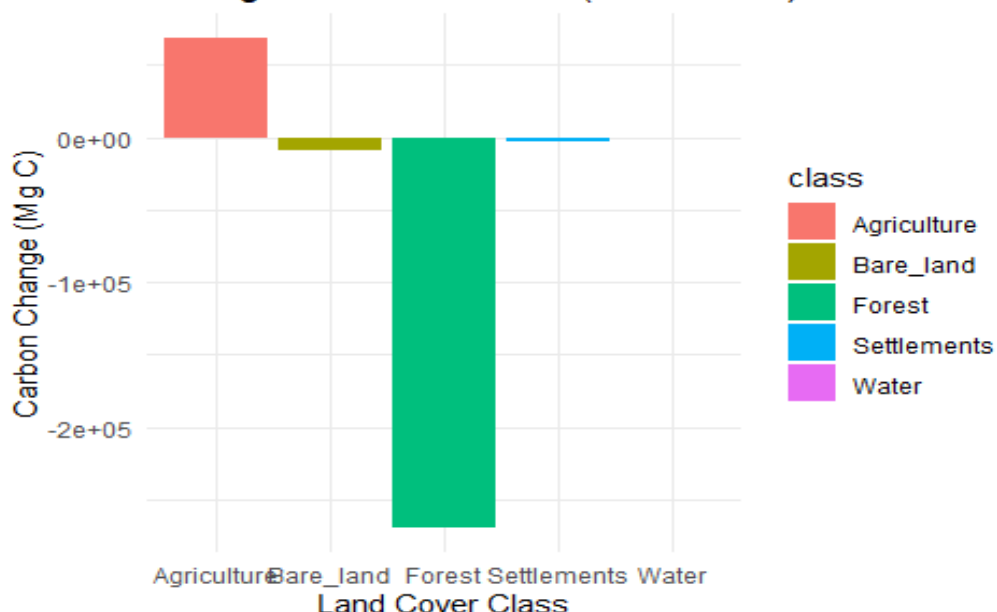




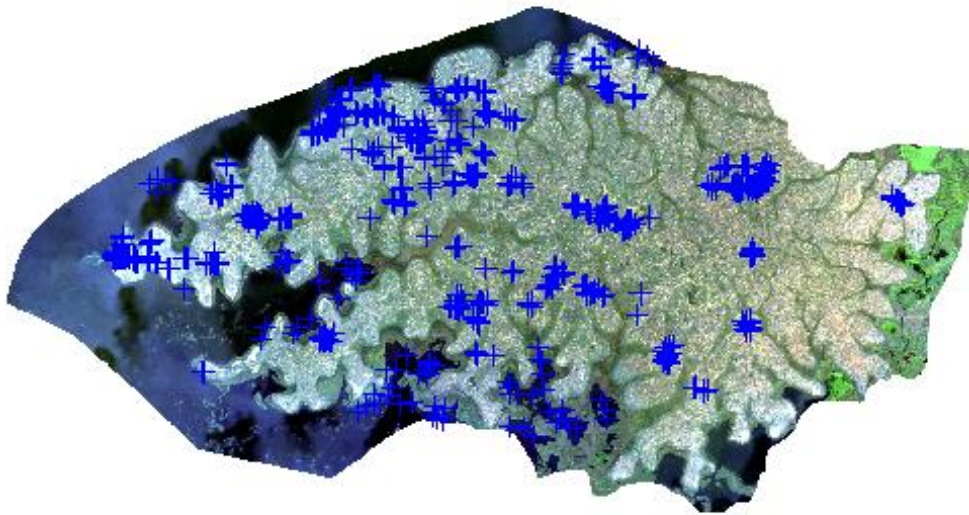
Land Cover Distribution in Forests by Year



Change in Carbon Stock (2001–2020)



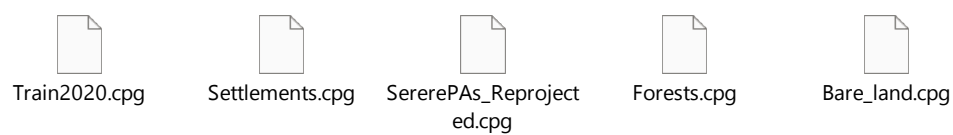
7. Data collection



8. Scripts: Custom R and Python scripts used to run and process InVEST outputs.



9. Description of field data collection for ground truthing.





Agriculture.cpg



Water.dbf



Training2020.dbf



Training_data.dbf



Train2020.dbf



Settlements.dbf



SererePAs_Reproject
ed.dbf



Forests.dbf



Bare_land.dbf



Agriculture.dbf



Water.cpg



Training2020.cpg



Training_data.cpg