KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,

KUMASI, GHANA

IMPACT OF LAND USE LAND COVER CHANGE ON CARBON STOCKS AND FOREST PRODUCTS-RELATED LIVELIHOODS IN THE CENTRAL AND UPPER RIVER REGIONS IN THE GAMBIA

By

Baba Drammeh

(BSc. AGRONOMY ENGINEERING; M. PHIL AGRONOMY)

A Thesis submitted to the Department of Civil Engineering, College of Engineering

In partial fulfillment of the requirements for the degree award of

Doctor of Philosophy in Climate Change and Land Use

October, 2025

DECLARATION

I hereby declare that this submission is my own work, and to the best of my knowledge and belief, it contains no materials previously published or authored by others, nor materials that have been accepted for any other degree or diploma at Kwame Nkrumah University of Science and Technology, Kumasi, or any other educational institution, except where proper acknowledgment is made in this thesis.

Baba Drammeh Signature Date: 08th October 2025
ID. PG6993121

Certified by:

Prof. Boateng Kyereh Signature Date:
(Supervisor)

Prof. Akwasi A Abunyewa Signature Date:
(Co-supervisor)

Prof. Walter Leal Filho Signature Date: 08th October 2025
(Supervisor)

Dr. Lamin B. Sonko Signature Date: 08th October 2025
(Supervisor)

Dr. George Ashiagbor Signature Date:
Supervisor

Prof. Richard Akwasi Buamah Signature Date:
Head of Department, Civil Engineering

ABSTRACT

In the Central River Region (CRR) and Upper River Region (URR) in the Gambia, forests, woodlands, and agroforestry systems have long sustained local livelihoods. However, increasing agricultural expansion, changing land use practices, and climate variability threaten these ecosystems, with significant consequences for carbon storage and livelihood security. Given communities' dependence on forest products for both subsistence and trade, ongoing LULC changes require a detailed scientific assessment. Understanding the dynamics of LULCC in these two regions and their implications for tree-based LULC and carbon stocks is essential for managing carbon emissions and enhancing ecosystem resilience to climate change. Since tree-based livelihoods share a common problem with climate change and climate variability, analyzing the two issues together provides a holistic way of addressing the concerns of LULCC and developing effective policies and strategies to slow and reverse the loss of tree cover. This study investigates land use and land cover (LULC) changes and their impact on aboveground carbon stocks and forest-dependent livelihoods in the CRR and URR from 2002 to 2024, with projections to 2034. Using Landsat imagery, supervised classification, and accuracy assessment in ArcGIS, the study identified four main LULC types: forest, grassland, cropland, and settlement. A stratified random sampling method was used, selecting 20 sampling points per LULC class in each region. Field data collection involved measuring tree diameter at breast height (DBH) with a diameter tape and tree height with a Sunnto clinometer within circular plots of 2,124 m^2. To assess livelihood dependence, a household survey was conducted with 396 respondents from both regions. Demographic data showed an average household size of 17.8 people, with ages ranging from 27 to 65 years and nearly equal gender representation. Multivariate probit regression indicated that gender significantly affected forest product use; men were more involved in using timber and thatch. Charcoal and firewood remained the dominant forest resources in both regions, though timber exploitation was higher in URR. The results show significant LULC transitions. Forest cover in CRR decreased by 95.2% to 310 hectares, and in URR by 85% to 127.8 hectares by 2024. Grasslands declined by 37.3% in CRR (to 165,729 hectares) and 40.6% in URR (to 116,763 hectares), mainly due to agricultural expansion. Croplands doubled in CRR (to 110,783 hectares) and increased by 82% in URR (to 74,794.68 hectares). Settlement areas grew by over 100% in both regions, reflecting rapid population growth and infrastructure development. Water bodies decreased by 12.3% in CRR and 19.4% in URR, likely due to upstream damming and irrigation pressures. Carbon stock analysis revealed notable forest carbon losses: in CRR from 11,059.72 tons (2002) to 23.49 tons (2034), and in URR from 378.89 tons to 12.32 tons. Grassland carbon decreased from 29,684.39 to 14,443.51 tons in CRR and from 14,162.60 to 6,983.52 tons in URR. Conversely, cropland and settlement carbon stocks increased significantly due to vegetation growth and urban greening. These changes highlight the profound effects of deforestation, urbanization, and agricultural expansion on regional carbon dynamics and ecosystem stability. The findings emphasize the urgent need for sustainable land management and climate-smart strategies. The study recommends combining satellite remote sensing with ground-based monitoring and predictive models to develop early warning systems. Promoting agroforestry and reforestation with native, multipurpose species can enhance tree cover and restore degraded lands while supporting local livelihoods.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Acronyms	**Definition**
AGB	Above Ground Biomass
BBRRS	Belize Barrier Reef Reserve System
BMBF	Federal Ministry of Education and Research
CAI	Comprehensive Agreement on Investment
CCLU	Climate Change and Land Use
CDM	Clean Development Mechanism
CRAN	Comprehensive R Archive Network
CRC	Cyclic Redundancy Code
CRR	Central River Region
CSE	Carbon Source Emission
DBH	Diameter At Breast Height
DEM	Digital Elevation Model
DOI	Digital Object Identifier
DRP	Directorate Research Program
ETM+	Enhanced Thematic Mapper Plus
FAO	Food And Agriculture Organization of The United Nations
FCC	False Color Composite
GEOMOD	Geometric Modeler
GHG	Greenhouse Gas
GIS	Geographic Information System
GPS	Global Positioning System
GWI	Global Warming Induces
HH	House Hold
IJCCSM	International Journal of Climate Change Strategies and Management
IPCC	Intergovernmental Panel on Climate Change
ISPRS	International Society for Photogrammetry and Remote Sensing
KNUST	Kwame Nkrumah University of Science and Technology
LCM	Land Change Modeler
LPG	Liquidity Petrol Gas
MEA	Millennium Ecosystem Assessment

ML	Milliliter
NARI	National Agricultural Research Institute
NASA	National Aeronautics and Space Administration.
NDVI	Normalized Difference Vegetation Index
OA	Overall Accuracy
OLI	Operational Land Imager
PA	Producer Accuracy
PCA	Principal Component Analysis
REDD	Reducing Emissions from Deforestation and Forest Degradation
RL	Reinforcement Learning
RVCDP	Regional Rice Value Chain Development Project
SOC	Soil Organic Carbon
STD	Standard Deviation
TIRS	Thermal InfraRed Sensor
UA	User Accuracy
UNCCD	United Nations Convention to Combat Desertification
URR	Upper River Region
UTG	University of The Gambia
WASCAL	West African Science Service Centre on Climate Change and Adapted Land Use
WGS	World Geodetic System
WRS	World Reference System

DEDICATION

This thesis is dedicated to my parents, Alhaji Kajali Drammeh and Aja Mama Samateh, my wife, Mrs. Aminata Samateh Drammeh, and my sons, Muhammed B. Drammeh, Yahya Drammeh, Mustapha Drammeh, Musa Drammeh, Abdul Rahman Drammeh, and Sheriff Drammeh, for their patience and understanding during this study.

ACKNOWLEDGEMENTS

Praise be to Almighty ALLAH! I am grateful for his guidance and blessings in having completed this work. This study is supported by a grant from the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) Programme on Climate Change and Land Use, funded by the German Federal Ministry for Education and Research (BMBF). I owe a lot of gratitude to my supervisors, Prof. Boateng Kyereh, Prof. Akwasi A. Abunyewa, Prof. Walter Leal, Dr. Lamin B. Sonko, and my mentor Dr. George Ashiagbor for their guidance, constructive criticism, which helped me to shape this thesis. My profound and special thanks go to Prof. Walter Leal, Hamburg University of Applied Sciences, Faculty of Life Sciences, Department of Health Sciences, Hamburg, Germany, for inviting me as a visiting scholar to analyse my PhD data and write papers for publication. I am also grateful to the entire staff of Kwame Nkrumah University of Science and Technology (KNUST) Kumasi, Ghana for being the lead university of hosting Climate Change and Land Use program. It is also my singular honour to thank the Director and the Coordinator of Climate Change and Land Use, Prof. Wilson Agyare, and Prof. Eric Forkuo, respectively and the WASCAL Climate Change and Land Use staff for providing the enabling environment and the academic support for this program. I wish to specifically thank Prof. Sidat Yaffa, Director of the Climate Change and Education program, WASCAL, The Gambia, for his input.

My profound gratitude also, goes to Dr. Mamma Sawaneh, PhD, Climate Change Economics WASCAL DRP, Scientific Coordinator Under the Directorate of the University of the Gambia (UTG), for his commitment to the achievement of this work. I want to thank Dr. Ebrima Sonko, Deputy Director of Renewable Energy Project The Gambia (RepGam). My appreciation also goes out to Dr. Jalamang Camara for his contribution to my research work. My special thanks go to my colleague Afi Amen Christele Attiogbe for her contribution to my Research. My sincere gratitude goes to the Entire Management and Staff of the National Agricultural Research Institute (NARI) of The Gambia for granting me a study leave to pursue this PhD program. My special thanks goes out to the Chairman, Mr. Sait Drammeh, for his continued prayers upon me. I also wish to express my sincere gratitude to my colleagues, the WASCAL CCLU PhD candidates, KNUST, who were the source of inspiration and hope during this program. My special thanks go to Dr. Enoch Bessah, KNUST Kumasi, for his

support throughout the study. Finally, I would like to thank My Wife, Aminata Samateh, who was committed to the family's welfare.

CHAPTER 1 GENERAL INTRODUCTION

1.1 Background

Land use land cover (LULC) refers to the ways in which humans utilize the Earth's physical and biological surface, including both natural and anthropogenic characteristics. Land use and land cover change (LULCC) is driven by human activities such as agriculture, urbanization, and resource exploitation (Keller and Soares, 2003; FAO, 2016). Global studies reveal that the proliferation of agricultural land adversely affects forests and grasslands, leading to a reduction in biodiversity and carbon sequestration (Ramankutty *et al.,* 2008; Crosson *et al.,* 2011). Fragmented landscapes hinder pollination, seed dispersal, and ecosystem resilience, whereas intensive land use exacerbates soil degradation (Bivand, 2015; Chernozhukov *et al.,* 2016). Global variances in land use and land cover changes are influenced by disparities in population growth, development, and environmental conditions (Liyew *et al.,* 2019). Between 2015 and 2020, Africa saw the most pronounced net forest loss, with an annual deforestation rate of 4.41 million hectares, equivalent to 0.69% of its forest area each year (Mekonnen et al., 2018). LULCC impacts the regional and global climate through greenhouse gas emissions and changes in surface reflectivity (FAO, 2016).

In The Gambia, primary LULC change drivers include agricultural expansion, tree felling for fuel, and settlement growth (Bah, 2019). Ceesay *et al.* (2017) linked deforestation to a 1°C temperature increase per decade since the 1940s and declining rainfall. National assessments show a 7% forest cover reduction from 1981 to 2010 (Nget *et al.*, 2011). In Central River Region (CRR), cropland expansion from 1984 to 2017 has been at the cost of savannas, largely due to declining soil fertility and low yields, which force farmers to clear new land, further contributing to CO_2 emissions and climate impacts (Sanneh *et al.,* 2022).

Tree-based ecosystems are vital for carbon storage and regulation, contributing to both above- and below-ground carbon pools. They supply organic matter through litterfall and root turnover and influence soil temperature, moisture, and erosion resistance, all of which enhance soil organic carbon (SOC) (Seddon *et al.*, 2020; Aabeyir *et al.,* 2020). Elevated temperatures may accelerate decomposition, perhaps resulting in carbon loss. Conversely, precipitation enhances biomass and carbon absorption (Hu *et al*., 2016). Nonetheless, alterations in weather patterns, such as droughts and other severe events, might impede crop cultivation and carbon sequestration (Villamor *et al*., 2017). Land utilization methods, including deforestation. Slash-and-burn techniques diminish the capacity of trees to sequester carbon; nevertheless, afforestation, replanting, and agroforestry provide avenues for ecological restoration (Haynes and Yongfu, 2014).

1.2 Problem Statement

In the Gambia's Central River Region (CRR) and Upper River Region (URR), tree-based systems, natural woods, plantations, and agroforestry have traditionally facilitated significant carbon sequestration. Nonetheless, increased agriculture and climatic unpredictability are transforming these ecosystems (Dampha, 2021). In particular, the introduction of the Rice Value Chain Development Project (RVCDP) in CRR and URR, which aims to increase rice production through technology adoption and farm expansion, is likely to distort the status quo, for whilst this project supports food security and income, it may detrimentally impact forest resources. Forests in these regions conserve carbon and provide essential ecosystem services and livelihoods, especially non-timber forest products (NTFPs), that are crucial for women and vulnerable groups (Msofe *et al.,* 2019; Sahoo *et al*., 2020). In The Gambia, the major drivers of land use and land cover changes are land clearing for agriculture, tree cutting for firewood and charcoal, and settlement expansions (Bah, 2019).

National forestry comparative evaluations for two periods (2009/2010 and 1981/1982) indicated a 7% decline in forest cover from 1981/1982 to 2009/2010 (Nget *et al*., 2011). Since 1984, agricultural extensification has notably affected many agroecological zones in the CRR. From 1984 to 2017, farmland areas increased, whilst shrub and woodland savanna areas diminished. This transition is mostly ascribed to land clearance for agricultural purposes, influenced by variables such as diminished soil fertility, which impedes plant growth and exacerbates CO_2 emissions. Farmers have said that diminishing soil fertility has resulted in decreased crop yields, necessitating the expansion into new territories to maintain agricultural output. Moreover, the application of chemical fertilizers, while widespread, is deemed costly and not consistently sustainable. The alterations in land use and processes of soil degradation are associated with heightened CO_2 emissions, intensifying the effects of climate change in the region (Sanneh *et al*., 2022). Ceesay *et al*. (2017) evaluated deforestation in The Gambia and determined that logging exacerbates climate change by causing a temperature rise of 1°C every decade since the 1940s and a decline in rainfall from 1950 to 2000. Deforestation operations in The Gambia must be monitored, along with their connections to climate change assessment, to enhance the knowledge of the country's climate change status.

1.3 Research Gaps

The factors contributing to anthropogenic climate change, mostly due to land-use practices, have garnered the interest of academics and stakeholders worldwide (Goldewijk and Ramankutty, 2004; Song and Deng, 2017; Seddon *et al.,* 2020; Temesgen *et al*., 2021; Chen *et al*., 2022). Despite increasing apprehensions over environmental degradation and land resource management in The Gambia, a notable deficiency persists in thorough, long-term evaluations of land use and land cover changes, especially in the Central River Region and Upper River Region. Current research frequently emphasises national or wider regional scales, exhibiting restricted temporal coverage or utilising old datasets that may not reflect modern trends and factors influencing land alteration. Furthermore, there is insuficient spatially explicit analyses that combine satellite images with ground-based data to monitor the temporal dynamics of land cover change. Given the significance of these regions for agriculture, biodiversity, and rural livelihoods, comprehending the evolution of land cover from 2002 to 2024 is essential for guiding sustainable land management methods, climate adaptation planning, and policy interventions specific to local settings. Furthermore, there has been insufficient investigation of tree-based carbon stock dynamics and mixed cropping systems involving intercropping with trees, while rice cultivation continues to be the predominant agricultural practice.

In the Gambia, forests and grasslands are being converted into rice fields for food security and livelihood for communities in CRR and URR, which has implications for climate variability and climate change on land use and land cover change. When forest cover is converted to rice fields, it would significantly impact carbon emissions and trigger erratic rainfall patterns, increase temperature, and reduce the ability of forests to sequester carbon due to land cover change. Moreover, other essential ecosystem services that the forest provides to these communities would also be lost.

1.4 Justification

Accurate information on LULCC is critical for understanding the causes of change and developing effective policies and strategies to slow and reverse deforestation Mekonnen *et al.* (2018). Concerns about LULC change consistently emerge in the reiterations of the research agenda on global environmental change. First, the influence of land-surface processes on regional climate is realised, and secondly, a modification of LULC change effect on surface-atmosphere energy exchanges is recognised. Land use land cover changes also partly determine the vulnerability of places and people to climatic, economic, sociocultural and political concerns, particularly in Sub-Saharan Africa (Naqvi and Athick, 2018; Solly *et al.* (2021) analysed the land cover change in The Gambia. They reported increased vegetation productivity with a significant trend along the river in almost all administrative regions of the country during the decade 2000-2009. However, a significant negative overall downward trend in productivity was observed between 2010 and 2019 in all administrative regions except the West Coast Region and Banjul. Considering the dynamics of LULC in an era of increasing climate change trends, it would be essential to understand the trends in LULC change and the way new development initiatives influence these trends.

1.5 Research Objectives

This study aims to assess the impact of LULC change on carbon stocks and forest-related livelihoods in CRR and URR of the Gambia.

The specific objectives were to:

(i) determine the Land use land cover change from 2002 to 2024 in the CRR and URR of the Gambia and predict LULCC from 2024 to 2034.

(ii) determine tree-based carbon stock dynamics from 2002 to 2024 in the CRR and URR in the Gambia; and predict carbon stock dynamics from 2024 to 2034.

(iii) assess the dependence of rural communities of the CRR and URR of the Gambia on forest products for livelihood.

1.6 Research Questions

(i) How did the land use land cover change from 2002 to 2024 in the CRR and URR of the Gambia, and what predictions can be made for 2034?

(ii) What are the dynamics of tree-based carbon stocks in the CRR and URR from 2002 to 2024, as influenced by land use and land cover type, and what are the projections for 2034?

(iii) To what extent do local people in the CRR and URR depend on forests for their livelihoods?

1.7 Limitations of the Study

The satellite data used in this research has a resolution of 30 m. While it may be suitable for small-scale studies, it isn't ideal for detailed investigations. Because higher-resolution photos are expensive, the study had to rely on free Landsat images of medium quality, which affects accuracy. The rainy season offers the most vibrant rural green spaces, as the rain enhances the greenery compared to the dry season. However, due to overcast conditions, obtaining predicted data from the wet season proved impossible. Instead, the information was gathered between late March and early April. Under the forest canopy, built-up areas can sometimes be overlooked. Given that the smallest pixel size is 30 m, small-scale green spaces cannot be captured; consequently, the research may have missed numerous small forest patches or roadside trees, leading to inaccuracies. Another limitation is that the study assumes the tree densities in the various LULC types have remained the same from 2002 to 2024, which is very unlikely. These were the limitations of the study.

1.8 Thesis Structure

This thesis consists of seven chapters. Chapter 1 presents the general introduction, giving an overview of the importance of climate change, LULCC through natural and anthropogenic actions, and of LULCC as a second source of carbon dioxide emissions. Chapter 2 covers the review of available literature that forms the theoretical and conceptual framework of the study. Chapter 3 addresses specific objective 1, which assessed the land use and land cover change from 2002 to 2024 in the CRR and URR of the Gambia, and predicts the change from 2024 to 2034. Chapter 4 addresses the specific objective 2: to analyse tree-based carbon stock dynamics in the CRR and URR in the Gambia. Chapter 5 deals with objective 3; the dependence of rural communities of the CRR and URR of the Gambia on forest products for livelihood. Chapter 6 presents the general discussion of the results, whilst Chapter 7 deals with general conclusions and recommendations.

1.9 Description of the Study Area

The study was conducted along the extensive floodplains of the River Gambia, located within the Central River Region (CRR) and Upper River Region (URR). Geographically, the area spans from longitude 15°27'43.905" W to 13°47'34.031"W and latitude 13°26'52.939"N to 13°38'19.187"N. It encompasses two of the country's primary agroecological zones: the Sahel-Savannah Zone, also known as the Semi-Arid Zone, and the Sudano-Sahelian or Riverine Zone. The Sahel-Savannah Zone, covering approximately 147,684 ha in the extreme northern part of CRR, is characterised by its semi-arid climate, with limited surface water availability and erratic rainfall patterns averaging below 900 mm annually. These climatic conditions render rainfed crop production particularly challenging and unreliable. According to soil suitability assessments, only 28% of the land is classified as suitable for cultivation, whereas 21% is marginal and 36% is deemed unsuitable for agricultural activities (von Luepke and Schoene, 2006).The combination of low and inconsistent precipitation, high evapotranspiration, and minimal water retention capacity of the soils further limits the region's agricultural potential. The Sudano-Sahelian or Riverine Zone, on the other hand, benefits from better water availability due to its proximity to the River Gambia, yet still experiences similar climatic challenges. These environmental constraints significantly influence land use practices and necessitate innovative agricultural strategies to improve food security and livelihoods in the region Brown, (1997).

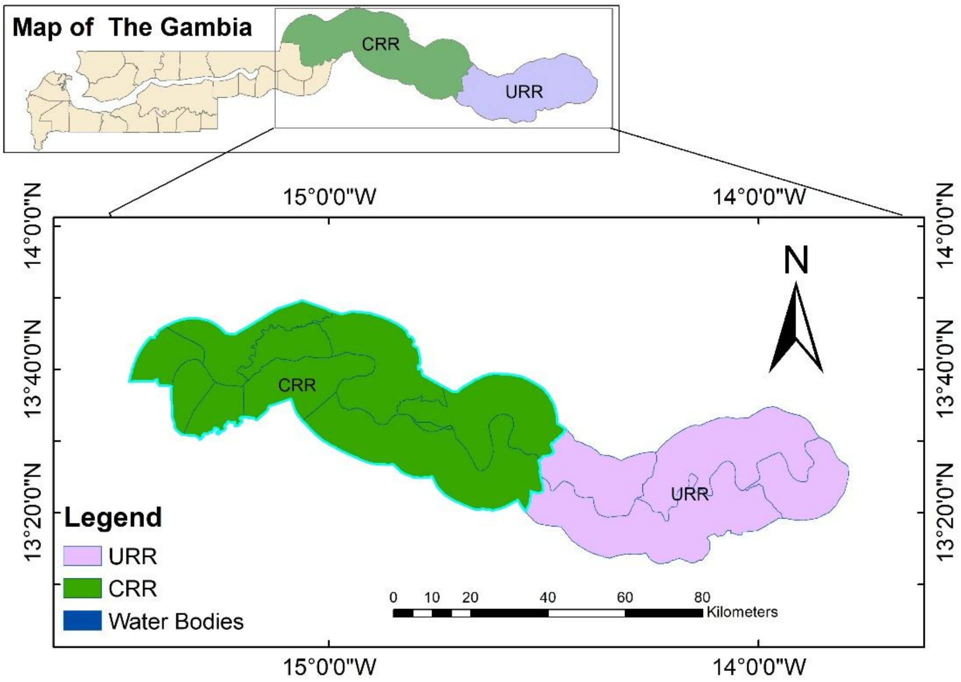

Figure 1.1: Map of the Gambia showing the study area, CRR and URR

CHAPTER 2 LITERATURE REVIEW

2.1 Concept of land use land cover (LULC)

Land use land cover refers to the physical and biological cover over the surface of the land as well as the human use of land for different activities. Land use land cover change (LULCC) is the term used for the human modification of the earth's terrestrial surface because of different human activities (FAO, 2016). Land use is a complex human-nature interaction, generating diverse social landscapes influenced to a greater or lesser extent by humankind. In particular, land used for urban areas and infrastructure puts pressure on ecosystem services due to continued soil sealing and the fragmentation of landscapes following continuous land conversion Hoffmann (2021). Consequences of land use change occur not only at the local or regional scale they are universally interconnected. Consequently, human action accelerates global change, which in turn impacts humankind. However, various partial models have been developed for different types of land use (Tarawally *et al.*, 2019).

2.2 Land use land cover change in West Africa

Rapid population growth has significantly altered land use patterns across West Africa. Between 2000 and 2020, the population in the region grew from approximately 650 million to over 1.1 billion, driving the expansion of agriculture into natural ecosystems (CILSS, 2016). A case study in Ghana revealed that cropland expanded from 10.7% of land area in 1975 to over 22% by 2013, underscoring how demographic pressures have led to the conversion of woodlands, savannas, and forests into farmland (Ampim *et al.,* 2021). Economic factors, particularly the shift toward cash-crop agriculture, have also had a transformative impact on land cover. From 2008 to 2015, Ghana's land under cash crops rose from 6% to over 30%, with this rise mirrored in other West African countries (Dahan and Kasei, 2022). The area of cashew plantations in Benin grew by almost four times from 2015 to 2021. Almost 60% of Crop land and fallow land have been replaced by cashew plantations in Benin (Martín-Arias et al., 2022). These trends show that the region is moving from subsistence farming to commercial export farming, which sometimes hurts natural vegetation. Urbanization and infrastructural expansion have put more stress on land resources, especially around big cities. In Ghana's peri-urban areas since 2005 urban growth and infrastructure improvements cut agricultural land by more than 55% in 2010 (Baffoe-

Andrews, 2024). From 1990 to 2020, urban areas in The Gambia and other coastal countries grew by roughly seven times, which caused a big loss of agricultural land and green spaces (Dibba *et al.,* 2025). These changes show how urban growth and land set aside for farming or natural ecosystems are at odds with each other. Changes in land use become more pronounced due to climate variability. Droughts are becoming more often, rain patterns are changing, and temperatures are rising, especially in the Sahelian region. This has made arable land less useful and forced people to turn woodlands and grasslands into farmland to make a living (Coulibaly, 2021). This tendency makes the environment worse and pushes people to move from rural areas to cities in search of new ways to make money (Wolde *et al*., 2023). Land use trends are also affected by institutional and governance considerations. In Ghana and Nigeria, weak land tenure regimes and poor implementation of rules lead to unregulated deforestation, agricultural growth, and charcoal manufacture (Buabeng et al., 2025). Governance defects make many environmental and economic problems worse, making it harder to manage land resources in a way that is good for the long term. Bah (2019) says that the main causes of land use and land cover change (LULCC) in The Gambia include clearing land for farming, cutting down trees for firewood and charcoal making, and expanding cities. Land clearance for farming is the main cause of land use and land cover change (LULCC), especially in rural regions like the Upper River Region (URR) and the Central River Region (CRR). In many places, farming is the main source of income, and as the population grows, the need for more farmland grows as well. The increasing use of low-input farming and shifting cultivation means that new ground is always being cleared, which is frequently bad for forests and woods. This action not only cuts down on tree cover, but it also hurts the soil and lowers the number of different kinds of plants and animals (Bah, 2019). Second, cutting down trees for firewood and charcoal manufacturing is a major cause of forest degradation. Biomass is still the predominant source of energy for homes in The Gambia, especially in rural and peri-urban regions. More than 70% of families use firewood and charcoal to cook, which puts a lot of stress on natural flora since they require wood for fuel. Cities like Banjul, Serrekunda, and Brikama are now the main places where people want charcoal, which makes commercial deforestation worse. This tendency is especially worrying in the Western Region, where better access and adjacent markets have made extraction faster (Bah, 2019). Thirdly, urbanisation and internal migration are quickly expanding settlements, which is changing land cover all throughout the country. More people are moving to cities, especially on the West Coast (WCR), which has led to a greater need for homes, infrastructure, and public services. This trend has turned agricultural fields, forests, and even protected areas into developed landscapes. This tendency has gotten worse because of the growth of informal settlements and the lack of good land-use planning frameworks (Bah, 2019; UN-Habitat, 2020).

2.3 Climate change and land use land cover

Climate change and uncertainty pose significant threats to terrestrial systems, particularly in ecologically sensitive or socioeconomically vulnerable regions, such as The Gambia's Central River Region (CRR) and Upper River Region (URR). The land systems, which include forests, farms, wetlands, and rangelands, are closely related to weather patterns such as rainfall, temperature, and severe weather events. Climate change changes where plants grow and how many of them there are. Changes in rainfall patterns and rising temperatures might lead to desertification and the decline of rangelands, especially in areas that are only partially dry (Lee *et al.*, 2022). It also causes species to move or go extinct because of changing weather patterns (Rookmaaker, 2020), and it changes how land is used and covered (LULC). For example, climate-induced migration can cause forests to turn into shrublands or agriculture to spread into areas that were once uncultivated. Climate change and changes in how land is used have had an effect on developing countries. Climate change, lack of water, and droughts that happen again and again have been very important. Fear of dry and semi-arid areas. These slow-moving risks are a big threat to the lives and food security of people in rural areas who depend on water. Climate change is also expected to make droughts happen more often, last longer, and be stronger (Yigini and Panagos, 2016). Artificial LULCC is a big factor. Changes in the surface of the land are the main cause of global and environmental decline (Prestele et al., 2017). Anthropogenic alterations in land use and land cover influence the biogeochemical and biophysical processes that drive climate change (Solly *et al.,* 2021). LULCC has been previously evaluated as a substantial carbon source emission (CSE). The updating of farming methods, such as raising animals and growing crops the modernization of farming methods, such as raising animals and growing crops, as well as the extensive use of agrochemicals, adds a lot to emissions. This raises the levels of CH_4 and N_2O in the air even more (Fuchs *et al.,* 2018; Heng, 2021). These actions can turn the land into a possible net source of greenhouse gases that go into the air (Banger et al., 2015). There have been observational studies in the area and the surroundings. Land use and land cover change (LULCC) affects biophysical surface properties, which in turn affect temperature and rainfall patterns (Msofe *et al.*, 2019). Forests, which cover around 30% of the Earth's surface, are particularly important for fighting climate change and giving everyone the benefits of ecosystem services (Biro et al., 2013; Dampha, 2020). Ecological services denote the benefits people obtain from ecological activities and ecosystem processes (Flade *et al.*, 2020), encompassing both direct and indirect advantages. Ecosystems significantly improve human well-being (Chishugi *et al.*, 2021). Ecosystems provide a wide range of goods, such as food, wood, and other natural resources. They also offer services that aren't physical, including managing water and storing carbon. Ecosystems do non-material things, including storing carbon, cleaning water, and making things seem better (MEA, 2005). The ES is widely used and shows how much people depend on natural ecosystems for their health and happiness (MEA, 2005; Sutton *et al.*, 2016). Forests provide a wide range of ecological services. More than 30% of the Earth's land surface is covered by forests. AO, 2016. Forest ecosystems provide a wide range of functions, including cultural, sustaining, regulating, and provisioning. Cultural services are services that are important for human survival and economic health (Aabeyir *et al.*, 2020). They are very important for keeping ecosystems going and making sure that important processes happen. Emiru *et al.* (2018) say that woodlands are very important for a number of ecological functions. Estuaries are very important for the diversity of life on Earth. Forests store more carbon than Woody biomes hold onto most of the carbon that is stored, unlike other ecosystems on land. (Murtishaw *et al.*, 2006; Pan, 2020) Zanne *et al.* (2009) say that forests are very important for slowing down climate change because they store carbon dioxide from the air as biomass, which lowers the amount of greenhouse gases (GHGs) in the air. The amount of carbon stored in forests changes depending on where and when they are, as well as the type of forest, its size, its age, its stand structure, and other factors. Walker et al. (2012) looked at plants and other environmental factors. Understanding these differences and how they affect the severity of the outcomes of aafforestation and improved forest management can reduce greenhouse gas emissions. Management is essential for directing plans for managing forests (Swamy et al., 2023). Still, the supply of valuable goods and services that forests give is going down because of deforestation and forest degradation. It is a big job to deal with deforestation and forest degradation in developing countries, where population growth and overuse for fuel and export are the main causes (Thiam *et al.*, 2022). Preserving forests and woodlands is an important way to reduce carbon emissions in a way that can last. Strategies to deal with the growing problems caused by global warming that the world is facing today (Muñoz-Rojas et al., 2015). Ecosystem and biodiversity services are declining worldwide, leading politicians to urge scientists to work together to come up with good policy responses. Encouraging scientists to work together to find effective policy solutions. Seddon *et al.* (2020) reported that several experts contend the human population is rapidly increasing, and owing to changing consumption and growth trends, individuals are influencing ecosystems worldwide. Recent research has demonstrated that the accessibility of ecosystem services and biodiversity declines with heightened land use intensity. There is a lot of disagreement among scientists on what the difference is. Meyer *et al.* (2025). Strategies that may be essential for protecting biodiversity and ecosystem services. Establishing and effectively managing protected areas are crucial for conserving biodiversity and maintaining ecosystem services (Watson et al., 2014). Promoting sustainable land use practices, such as agroforestry and organic farming, helps reduce habitat destruction and improve ecological balance (Jose, 2012). Restoring degraded ecosystems through reforestation, wetland rehabilitation, and soil restoration enhances ecosystem resilience (Aronson and Alexander, 2013). Implementing policies that regulate the overexploitation of natural resources, including logging, hunting, and Seddon *et al.* (2020) and Ceesay *et al.* (2017) looked at deforestation in The Gambia and found that logging makes climate change worse. Logging makes climate change worse by raising temperatures by 1°C every decade since the 1940s and lowering rainfall from 1950 to 2000. The effects of climate change and the growth of farming have long-lasting effects on the ecosystem that are bad for forests all around the world. Ochuka *et al.* (2019). The biggest places on land where carbon is stored are in forest ecosystems. People on Earth have recognised that managing them is a cost-effective way to cut down on greenhouse gas emissions. Forests cover over a third of the land surface, and they store roughly three decades' worth of carbon dioxide (CO_2) from fossil fuels used in the economy (FAO, 2016). The state of forest loss is not universal, however. The role of forests in emissions. Since 2005, offsets from forestland in the United States have stayed fairly stable, despite many changes in land management practices and economic activities. Early decreases in CO_2 emissions across the economy during that time were mainly due to better energy efficiency, a shift from coal to natural gas, and there was an increased reliance on renewable energy sources, while forests continued to act as a consistent carbon sink (FAO, 2016).

This suggests that forest C sinks in the United States are improving, which is driven in large part by forest regrowth following harvest and natural disturbance (FAO, 2016).

Drought is one of the most troublesome natural threats that affects millions of people worldwide each year and imposes substantial challenges on the environment, economy, and society. It is considered the most devastating natural disaster due to its prolonged and widespread socioeconomic impacts (Liyew *et al.,* 2019). Drought impacts can either be direct, e.g., restrictions on water use or decreasing crop yield, or indirect, e.g., increasing food costs due to decreased crop yield (Arfasa *et al.*, 2023). Droughts impose an average of $6–8 billion in damage to the United States each year (Allaire *et al.*, 2013). It has been reported that drought damages in Europe during the past three decades have exceeded €100 billion (WMO, 2005; Ahmadalipour *et al.,* 2019). While wealthy industrialised nations are considerably affected by the economic impacts of drought, their social impacts are remarkable in food-scarce developing countries with high dependency on agriculture (Sanneh *et al.,* 2022). Climate change through global temperature rise will have significant impacts on natural hazards, extreme events, the economy, and health, as stated by Ahmadalipour *et al.* (2019).

A multitude of studies have investigated the impacts of climate change on drought in various parts of the globe (Sanneh *et al.,* 2022). Climate change will intensify drought hazards in many regions across the world (Ahmadalipour *et al.*, 2019). This is especially more considerable in arid and semi-arid regions as global warming will, in general, increase the potential evapotranspiration (Muñoz-Rojas *et al.*, 2015). The impacts of climate change and population growth are also expected to augment natural resource scarcity and food insecurity in Africa (Emiru *et al*, 2018). Population growth affects drought risk both directly, i.e., through increasing the exposure component of the risk, and indirectly, by aggravating drought vulnerability (Ahmadalipour *et al.*, 2019). The increasing population will demand additional resources of food, energy, and water for sustainable growth. Knowing that drought can significantly affect agriculture, energy, and water supply (Villamor *et al.*, 2019), raising the population will directly increase the risks of drought due to the increasing demand. In addition, the increasing population can have negative impacts on measures of social vulnerability (Swamy *et al.*, 2023).

2.4 Land use land cover and land degradation

Land degradation is becoming increasingly evident and is expensive, both to local owners and to society in general, over multiple time and space scales (van Esch *et al*., 2017). The United Nations Convention to Combat Desertification (UNCCD), at RIO+20, set a zero net land degradation target (Sutton *et al.*, 2016). The need to restore degraded lands and prevent further degradation is critical, meanwhile the demand for accessible, productive lands is increasing (Sutton *et al.*, 2016). These changes are projected to affect mainly tropical regions that are already vulnerable to other stresses, including the increasing unpredictability of rainfall patterns and extreme events as a result of climate change (Martín-Arias *et al.*, 2022). Land degradation is a consequence of the poor management of natural capital (soils, water, vegetation, etc.). According to Sutton *et al.* (2016), better frameworks are needed to (i) quantify the scale of the problem globally; (ii) calculate the cost of business-as-usual, and (iii) assess the costs and benefits of restoration.

Farmers and business leaders realise that ecosystem degradation is a material issue that affects their bottom line and future prosperity (Sohrabi *et al.*, 2016). However, they lack the decision-making tools to develop robust and effective solutions to the problem. Modelling and simulation techniques enable the creation and evaluation of scenarios of alternative futures and decision tools to address this gap (Sutton *et al.*, 2016). Ecosystem services, including but not limited to agricultural products, clean air, fresh water, disturbance regulation, climate regulation, recreational opportunities, and fertile soils, are jeopardised by the effects of land degradation globally (Yigini and Panagos, 2016).

2.5 Impact of Climate Change on Agriculture and Food Security

The amount of food that can be cultivated and the stability of the soil are both affected directly by changes in temperature and rainfall. In locations where people farm without irrigation, it can be challenging to raise food since the growing seasons are short or impossible to forecast. Evapotranspiration and lengthy dry spells make soil erosion and nutrient loss worse. Trees are under increasing stress because of new farming methods (Francis and Sena, 2022). Climate change is a major danger to the West's ability to generate food and feed its people. A lot of people in Africa rely on smallholder and subsistence farming to make a living. The area is quite susceptible to fluctuations in temperature and rain since farming needs rain to irrigate crops. Climate change is changing the weather, so it rains later, crops grow for shorter periods of time, and droughts happen when they shouldn't. This has a huge influence on the soil's health, its capacity to grow food, and the overall process of creating food. Well-being and happiness are strongly influenced by social, economic, and environmental factors, which play a key role in shaping human development and resilience (Rippke *et al.*, 2016; Sultan and Gaetani, 2016). The temperature and rainfall change, which dries up the soil, make more water evaporate, and makes long droughts happen more often. This is especially true in the Sahel and Sudan regions. These weather patterns wash away nutrients and make the soil become a desert, which makes the land less useful. Amjath-Babu et al. (2023) and Serdeczny et al. (2017) demonstrate that certain farmers in West Africa alter their agricultural practices by relocating to regions with diminished profitability or forestry. This affects the land and means that more trees need to be chopped down. When the weather changes abruptly, it also throws up the routines for traditional farming and the methods that native people share information. This is often used by smallholder farmers to assist them decide when to plant and when to harvest. Farmers in northern Nigeria and Burkina Faso can't determine when the rainy season starts because the way it rains has changed. This is why seeds don't grow and plants die (FAO, 2019). Climate change makes it tougher for farmers and those who care for animals to get enough food and water. This makes it more probable that the two sides will battle. Poor individuals are more likely to fail, especially if they don't have enough resources, a solid infrastructure, or excellent extension programs. Limited access to agricultural resources, poor infrastructure, and not enough extension services are all examples of socioeconomic restrictions (Morton, 2007; World Bank, 2020). When you can't guess how much food will be created, prices go up a lot. impacting families with low incomes who spend a lot of money on food. This makes it worse for mothers and children who are hungry and don't have enough food. There have been food shortages in Mali, Niger, and northern Ghana in the past few months because of long-lasting droughts and low crop yields. This demonstrates how rapidly harsh weather may mess up food systems (UNDRR, 2020).

2.6 Land use, land cover decisions and adaptation in agrarian communities

Climate fluctuation affects how land is planned and managed. Communities adapt by moving farming into wooded regions, switching to crops that can handle climate change, practicing agroforestry and conservation tillage, and using methods that cut emissions and make them more resilient at the same time (IPCC, 2021). Climate variability has a big effect on how land is used in West Africa. Communities are changing how they manage their land more and more because of unpredictable rainfall, rising temperatures, and frequent droughts.

One big change is that farmers are moving into forests and marginal regions because their yields are going down. This frequently leads to deforestation and soil degradation, particularly in nations such as Ghana, Burkina Faso, and Nigeria (Serdeczny *et al.,* 2017; Amjath-Babu *et al.,* 2023). Farmers are also converting to crops that can handle climate change, such early-maturing and drought-tolerant types, to deal with shorter growing seasons and unpredictable rainfall patterns (Rippke *et al.,* 2016; Sultan and Gaetani, 2016). Agroforestry is also becoming more popular as a way to manage land sustainably. It provides shade, improves soil moisture, and adds variety to revenue through tree products. The Great Green Wall and other projects are helping to promote agroforestry and sustainable land restoration across the Sahel (FAO, 2019; UNCCD, 2020). Conservation agriculture methods like minimum tillage, contour farming, and soil water retention structures are also being used to restore degraded land and increase productivity. These behaviors help people adapt and cut down on emissions at the same time, which is in line with national adaptation and mitigation policies under NDCs and NAPs (IPCC, 2021; UNFCCC, 2020).

Climate change has a big effect on how people utilize land in West Africa, especially The Gambia. Communities are changing how they manage land to deal with unreliable rain, rising temperatures, and long dry periods. A widespread reaction in the region is the encroachment of agricultural boundaries into wooded and marginal regions, driven by diminishing production on current farms that compels farmers to pursue new cultivable territories. This tendency has been seen in The Gambia, especially in rural areas like the Central River Region (CRR) and the Upper River Region (URR). It has led to deforestation and a loss of biodiversity (Bah, 2019; Amjath-Babu *et al.*, 2023). To adjust, many farmers are switching to crops that can handle climate change, such millet that can handle drought, early-maturing groundnut types, and sorghum, which are better for growing seasons that are shorter and rain that is less consistent.

Senegal, Mali, and Burkina Faso, which are close by, are also seeing similar developments. This shows that the area is moving toward more robust farming systems (Sultan and Gaetani, 2016; Rippke *et al.*, 2016). Agroforestry is becoming an important way to adapt in both The Gambia and West Africa as a whole. Adding trees to fields makes the soil more fertile, provides shade, slows down erosion, and gives families more ways to make money. In The Gambia, community forest management and tree planting initiatives supported by national policies align with broader Sahelian efforts such as the Great Green Wall (FAO, 2019; UNCCD, 2020). Moreover, conservation agriculture techniques, including reduced tillage, contour ploughing, and the use of water-harvesting pits, are helping to rebuild degraded soils and improve water retention. These practices are promoted by both the government and development partners in The Gambia as part of climate-resilient agriculture efforts (IPCC, 2021). While some strategies, such as forest clearing, offer short-term adaptation benefits, they may undermine long-term environmental sustainability. Therefore, integrated land use planning, strengthened institutional support, and access to climate information are essential to guide adaptive decisions that both build resilience and support climate mitigation in The Gambia and across the West African region (Bah, 2019; UNFCCC, 2020) .

2.7 Land use, land cover and carbon stocks

Carbon in terrestrial ecosystems is stored in several pools: Aboveground biomass (AGB), living trees, shrubs, and herbaceous vegetation; Below-ground biomass (BGB), roots; Dead organic carbon (DOC), deadwood, litter; Soil organic carbon (SOC) in topsoil and deeper layers. Carbon storage is roughly 50% of biomass mass; thus, biomass estimates are converted to carbon using this factor. Steffens *et al.*, (2022) found that plant diversity, wood density, mycorrhizal associations, and nitrogen-fixing ability significantly affect soil and forest-floor SOC stocks. In an Eastern Ethiopia study, a large variation in AGC, from ~7 to 71 t C/ha across land cover types was reported, with riparian forests having the highest stocks (~71 t C/ha). In Tanzania, mangroves had some of the highest total carbon stocks (including AGC, BGC, DOC), while wetlands and non-forest classes showed significantly lower levels (Steffens *et al.*, 2022). Biomass is a reliable proxy for carbon storage; AGB often dominates, but combining soil and deadwood pools provides a complete picture.

2.7.1 Impact of LULC Types on Carbon Stocks

Different land use types influence carbon storage; forests store the most carbon across all pools. Woodlands and agroforests exhibit moderate levels of aboveground carbon (AGC) and soil organic carbon (SOC) storage, while croplands, grasslands, and shrubland retain considerably less. In Burkina Faso, woodlands recorded approximately 10 Mg C/ha in biomass, and gallery forests around 7.8 Mg C/ha, with croplands and savannas holding less than 2 Mg C/ha. In another study, gallery forests excelled in SOC, averaging about 30 Mg C/ha (Dayamba *et al.*, 2016). In Ethiopia's Afromontane region, forests contained notably more carbon compared to grasslands and farmland; conversion from forest to agricultural land resulted in reduced carbon levels in AGC, belowground carbon (BGC), dissolved organic carbon (DOC), and SOC. Specifically, in the Upper Awash Basin of Ethiopia, forests had an AGC of approximately 259 t C/ha, while croplands registered around 41 t C/ha (Steffens *et al.*, 2022). In Ghana, forest soils were found to possess higher SOC, greater moisture, and reduced compaction compared to arable lands (Kumi-Boateng *et al.*, 2015). Overall, land use and land cover (LULC) changes driven by degradation, such as deforestation and cultivation, significantly diminish carbon stocks.

2.7.2 Importance of the Aboveground Carbon Stock compared with other sources of carbon stocks

While AGC is often emphasized, a holistic approach considers all carbon pools: AGC is dynamic and easier to measure; it is a key carbon sequestration indicator. SOC, however, particularly in grasslands and wetlands, can exceed AGC and remains more stable over time. Although AGC offers rapid insight, long-term carbon storage requires accounting for SOC and DOC, particularly in non-forest ecosystems and wet/dry transition zones (Dayamba *et al.*, 2016).

2.7.3 Studies on Carbon Stock Dynamics globally and in West Africa

Understanding the relationship between land use and carbon stocks is crucial for informing climate mitigation strategies, particularly in tropical and sub-Saharan ecosystems, where land cover transitions are frequent and have a significant impact. Land use and land cover (LULC) changes influence carbon storage both above and below ground. Vegetation and soil are the primary reservoirs of terrestrial carbon, and their management has a direct impact on atmospheric carbon concentrations. Globally, mangrove ecosystems are among the most carbon-dense habitats. In 2012, mangroves had around 4.19 petagrams (Pg) of carbon, most of which was in the ground. Between 2000 and 2012, people cut down 2% of the world's mangroves. According to Rimal *et al.* (2018), these trees let out roughly 317 million tonnes (Mt) of CO_2. This shows how important it is to protect coastal areas since they are home to many plants and animals and help keep the weather stable. Many people think that the woodlands in Lower Guinea, West Africa, have a lot of biomass. They are particularly good at retaining carbon. It's a beneficial idea to keep carbon in grasslands, especially as soil organic carbon (SOC). Grasslands are thought to have approximately 20% of the world's SOC, which is more than 20% of the world's carbon. Rimal *et al.* (2018) assert that around 81% of the carbon within an ecosystem is sequestered in the soil layers and roots, rather than in the above-ground vegetation. This shows how important it is to keep an eye on underground carbon storage, especially in dry, grassy areas. Recent research indicates that the quantity of vegetation and land influences the carbon sequestration capacity throughout time. Steffens *et al.* (2022) assert that the functional characteristics of trees, including their mycorrhizal associations and nitrogen-fixing capabilities, significantly influence global soil carbon storage.

These factors change how nutrients circulate, how much root biomass there is, and how active bacteria are. This is why the amount of organic carbon in the soil changes from biome to biome. Trees are still very important for retaining carbon in the ground in West Africa. Kucuker *et al.* (2015) say that the trees in the area absorbed about 38.9 Mt of carbon each year in 2018. People think that this kind of greenhouse gas made for around 15% of the greenhouse gases that were generated in the area in 2017. They also claimed that planting trees and cultivating food in forests every year may add 27.5 million tons of carbon to the atmosphere. This shows that recovering land can help keep the area's climate stable. We've come a long way in the last several years in how we maintain track of and map carbon stocks. The 2017 USGS West Africa Land Use and Land Cover (LULC) series has maps that are the same for 1975, 2000, and 2013. Scientists and policymakers may use these maps to find out more about how the land has changed over time and how those changes have affected the amount of carbon stored in the ground. The cocoa agroforestry systems in Côte d'Ivoire might contain between 11.7 and 36.9 tons of carbon per hectare, depending on how well the trees are cared for and how many various kinds of trees there are (Côte d'Ivoire Ministry of Environment, 2024). The SERVIR-West Africa S-CAP project in Ghana has also used data from satellites and the ground to learn more about how making charcoal affects the loss of biomass. This helps us understand why some places lose carbon (SERVIR S-CAP, 2024). It is becoming obvious that utilizing simply above-ground biomass (AGB) to figure out how much carbon there is may not offer a whole picture of how much carbon there is. To gain a better overall view, you need to mix together dissolved organic carbon (DOC), soil organic carbon (SOC), and aboveground biomass (AGB). This is especially true in grasslands, marshes, and woodlands. Cutting down trees, growing more crops, and making charcoal are all ways that humans utilize land that normally lower the amount of carbon in the atmosphere. But items that are good for the environment are Rimal *et al.* (2018) believe that growing trees, agroforestry, and making the soil better can all help it hold on to more carbon.

2.7.4 Forest and Tree-Based Livelihoods

People in the Global South, especially those who live in sub-Saharan Africa, really adore trees and forests. They provide us things that are good for the environment, such food, medicine, fuel, and wood. You may utilize these right now or sell them for cash (Kuyah *et al.*, 2020). People in The Gambia derive most of their charcoal and fuel from trees. These are very significant for the economy and for providing people in rural areas more power (Dibba *et al.*, 2021). Agroforestry and other farming methods that incorporate trees can help households stay healthy. These programs assist families acquire more money and make sure they have enough food and nutrients (Mbow *et al.*, 2014). You may make money all year long by selling non-timber forest products (NTFPs). NTFPs include nuts, fruits, leaves, and resins. They can help crops stay alive and stop the market from shifting too rapidly (Shackleton *et al.*, 2011). Parkia biglobosa (African locust bean) and Vitellaria paradoxa (shea tree) are important to the economy of West Africa's dry areas. Women frequently convene to create them (Coulibaly, 2021; Baffoe-Andrews, 2024). Even if they are, national economic figures don't often show how vital these resources are for the health of families and forests. It's very important to observe the regulations and customs of the area for many occupations in the forest. In certain areas, traditional tenure patterns control these jobs and have an effect on how land is utilized and how simple it is to get there (Chomba *et al.,* 2016). Changes in the weather, how land is used, and cutting down trees all put these occupations at jeopardy. People are making the forest smaller by chopping down trees, farming, building roads, and doing other things. The forest is getting smaller because of this makes it tougher to receive items and services from the forest (Ampim *et al.,* 2021; Wolde *et al.,* 2023). If we want to accomplish sustainable development, policies need to include better forest management and make sure that people are healthy and happy. Community forest management, agroforestry, and payments for ecosystem services (PES) are good for both people and the environment (Dahan and Kasei, 2022; Martín-Arias *et al.,* 2022). Improving the safety of forest tenure and the value chains of non-timber forest products has a lot of benefits. This initiative allows individuals in rural regions, notably women and other groups who are frequently left out, greater power. The food that these cultures eat comes from the forests.

2.8 Methods for LULC Classification, Carbon Stock Measurement, and Inventory

2.8.1 Land use, land cover (LULC) Classification Method

Accurate Land Use and Land Cover (LULC) in the right order is very important for showing how the ecosystem changes over time and space. Land Use and Land Cover (LULC) classification provides the basis for ecological, hydrological, and socio-economic models, especially in places where land is changing swiftly because of human and natural factors (Lu and Weng, 2007). Researchers at LULC have employed a lot of different ways to arrange things, from older pixel-based approaches to current object-based and machine learning methods. Many people employ supervised classification methods like Maximum Likelihood Classification (MLC), Support Vector Machines (SVM), and Random Forest (RF) because they can use training data to generate predictions about classifications in regions that haven't been investigated before (Foody, 2002). MLC works well when the data is mostly spread out and not too expensive to handle. But it could not be as accurate if the data is jumbled up or not Gaussian (Richards and Jia, 2006). On the other hand, SVM and RF don't need strict statistical assumptions and usually do a better job of classifying, even when the scenarios are quite different (Pal, 2005). Two examples of unsupervised classification algorithms are K-means and ISODATA. They group pixels together based on how similar their colors are. They can begin without any training data. These tactics are effective in data-scarce environments, however the rationale behind their efficacy may remain ambiguous, necessitating subsequent categorization (Jensen, 2005). In the past several years, object-based image analysis (OBIA) has become more essential. Object-Based Image Analysis (OBIA) breaks images down into their most important parts and then puts them back together. Adding details about the place, the texture, and the situation makes the categorization more accurate (Blaschke, 2010). This approach works best with satellite photos that have a lot of detail. It is typically used in cities and woods. More and more people are using Convolutional Neural Networks (CNNs) and other deep learning approaches to categorize Land Use and Land Cover (LULC) because they can automatically extract out complicated spatial data from huge datasets (Zhu *et al.*, 2017). But they can't be utilized very often in impoverished nations since they need a lot of processing power and massive datasets that are easy to find. In the end, the research question, the data that is accessible, and the unique needs will determine how to categorize the information. More precise levels of classification. In countries like The Gambia, where it might be hard to get appropriate training data, a hybrid method that combines classical classification with contextual augmentation often performs effectively.

2.8.2 Carbon Stock Measurement Methods

Carbon stock measurement is critical in understanding the contribution of ecosystems to climate regulation and in designing mitigation strategies against greenhouse gas emissions.

2.8.3 Field Inventory Method

Field inventory methods are essential in assessing natural resources, especially in ecological and forestry research. These approaches involve directly measuring and observing vegetation traits such as species composition, tree diameter, height, and biomass within specific sample plots (Pearce *et al.,* 2001). Unlike remote sensing, field inventory offers highly accurate, ground-based data crucial for calibrating and validating. In terrestrial ecosystems, carbon is mostly stored in aboveground biomass, belowground biomass, dead organic matter, and soils (IPCC, 2022). Changes in land use and land cover directly affect these carbon stores. The conversion of forests to agricultural land frequently results in considerable carbon loss, whereas regeneration and agroforestry can enhance carbon sequestration. The assessment of carbon stock often relies on field data and default values based on IPCC guidelines. Field-based strategies utilize forest inventory data and allometric equations (Chave *et al.*, 2014), while modeling techniques like InVEST incorporate spatial land use and land cover (LULC) maps in conjunction with carbon density values assigned to each land cover category (Henry *et al.*, 2011). These approaches are especially beneficial in data-scarce regions like The Gambia, where dependable field observations are limited (Balde *et al.* 2014). The assessment of carbon stock was conducted using the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) carbon model. This spatially explicit model assesses carbon sequestration across four principal reservoirs: aboveground biomass, belowground biomass, soil organic carbon, and dead organic matter (IPCC, 2022; Henry *et al.*, 2011). The model combines Land Use/Land Cover (LULC) maps with carbon density measurements for each category, employing Tier 1 IPCC default values and pertinent literature. This method is especially beneficial for data-scarce areas like The Gambia, facilitating dependable estimates across both temporal and geographical dimensions. spatial models (Korhonen *et al.*, 2006). A systematic sampling design, often used in forest inventories, involves placing plots at regular intervals across the study area to ensure unbiased coverage. Alternatively, stratified random sampling is employed when the study area has distinct land cover types, allowing for more representative data within each stratum (Loetsch *et al.*, 1973). Plot sizes vary based on study goals and vegetation types; common dimensions include circular plots (e.g., 0. 0.1 ha) or rectangular plots suitable for dense forests or savannas

(FAO, 2004). During field inventory, key parameters recorded include diameter at breast height (DBH), tree height, crown cover, and species identification. These variables form the basis for estimating biomass, carbon stock, and diversity indices (Brown, 1997). Recently, allometric equations have been developed to convert field measurements into estimates of above-ground and below-ground biomass, which are vital for climate change mitigation efforts, especially in REDD+ projects (Chave *et al.*, 2014). Despite its accuracy, field inventory methods face limitations such as high labor demands, time consumption, and logistical challenges, particularly in remote or conflict-affected areas. Nonetheless, combining field data with remote sensing improves accuracy and supports landscape-level analysis (Goetz *et al.*, 2009). In land use and land cover studies in Sub-Saharan Africa, field inventory remains crucial due to limited access to high-resolution satellite data and issues like cloud cover. For example, in The Gambia, community-based inventories have been implemented to evaluate forest resources, promote participatory natural resource management, and supply data for national forest monitoring systems (FAO, 2013).

2.9 Justification for Method Selection

The methods employed in this study were selected for their well-established suitability in assessing land cover change and carbon stocks within tropical and sub-Saharan African landscapes. We employed supervised classification, namely the Maximum Likelihood Classifier (MLC), as it is more effective in distinguishing various land cover types in savanna and semi-arid regions such as CRR and URR. MLC has been extensively used in analogous ecological contexts and is recognized for its superior capability in managing spectrum overlap compared to unsupervised methodologies (Foody *et al.,* 2004; Lu *et al.,* 2007). We selected the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) carbon model because to its user-friendliness and aesthetic appeal. It utilises land cover data to ascertain the quantity of carbon present in the Earth. This is advantageous as it facilitates the utilisation of Tier 1 IPCC carbon estimates and aids in scenario analysis (Sharp *et al.,* 2020) in data-scarce situations. This is vital for regions such as The Gambia, where sufficient data on carbon inventories may be lacking. We employed a circular plot with a 26-meter radius for the field inventory due to its statistical validity and efficacy in remote areas with limited resources. This plot size allows field teams in African forests and savannas to get accurate biomass assessments (Hairiah *et al.,* 2001; Chave *et al.,* 2014). Accessing the CRR and URR by road was challenging, and there were limited supplies available in the area. Our technique ensured the appropriate representation of carbon pools according to their locations. It furthermore conserved time and effort.

CHAPTER 3 LAND USE AND LAND COVER CHANGE IN TWO AGRICULTURALLY IMPORTANT BUT ECOLOGICALLY CONSTRASTING ZONES OF THE GAMBIA

3.1 Abstract

This study investigates land use and land cover change (LULCC) in The Gambia's Central River Region (CRR) and Upper River Region (URR) from 2002 to 2024, utilizing satellite images and supervised classification methodologies. The study shows that land cover has changed a lot, mostly because of the growth of agriculture. Between 2002 and 2013, cropland increased by 53,698.86 ha. Settlements also grew significantly, expanding by 12,493.62 ha. Conversely, natural landscapes such as grasslands and forests experienced severe losses, primarily converted into farmland and settlements. Grassland cover declined by 48,672.36 ha from 2002 to 2013 and by 43,482.6 ha from 2013 to 2024. Forests also declined by (753.75 ha) from 2002 to 2013, (501.57 ha), and (351.18 ha) from 2013 to 2024. (127.8 ha). Future projections for 2024-2034 predict a net loss of 37,211.85 ha of grassland and a net gain of 32,090.13 ha in cropland in CRR. Similarly, in URR, cropland is expected to expand by 13,562.91 ha, while grasslands are projected to shrink by 19,930.95 ha. These findings highlight the intensification of land use determined by agriculture and rural development, emphasizing the need for sustainable land management practices to mitigate deforestation, habitat loss, and environmental degradation.

3.2 Introduction

Land use and land cover refer to the physical and biological features of the land's surface, as well as how people use the land for different things (Keller and Soares 2003). Land use and cover change (LULCC) is the change in the Earth's surface caused by different human activities (FAO, 2016). Recent studies emphasize the rapid expansion of agricultural land, adversely affecting forests, natural grasslands, and woodlands. Ramankutty et al. (2008) documented substantial increases in global agricultural land utilization, driven by the imperative to meet food production requirements for a growing population. This trend has led to a lot of deforestation and changes to habitats, which has affected carbon sequestration and sped up climate change (Crosson *et al.,* 2011). Changes in how land is used and covered have a wide range of implications. Forest fragmentation leads to the destruction of continuous ecosystems, which harms plant and animal species that rely on large, unbroken land expanses. This fragmentation reduces biodiversity and makes biological processes less effective, such as pollination and seed dispersion (Chernozhukov *et al.,* 2016). Intensive farming also harms the health of the soil, which leads to lower crop yields and makes the land more vulnerable to erosion and desertification (Bivand, 2015). Despite this, patterns of land use and land cover change have not been uniform over the world because different factors drive them. Changes in land use and land cover throughout the world have been caused by population growth, human activities, and development (Liyew *et al.*, 2019).

Reports say that Africa lost more than 4.41 million hectares of forest per year from 2015 to 2020. This means that at that time, the globe lost the most forest land. In 2020, Africa had over 636 million hectares of forest, and every year, about 0.69% of the continent's total forested area was cut down (Mekonnen *et al.*, 2018). LULCC may change the way the earth's surface reflects light, which can change the temperature in some areas and throughout the world (FAO, 2016). Bah (2019) says that the main things that affect changes in land use and land cover in The Gambia include clearing land for farming, cutting down trees for fuel and charcoal, and urban expansion. Ceesay *et al.* (2017) also looked at deforestation in The Gambia and found that logging makes climate change worse by making it worse.

Every decade since the 1940s, temperatures have gone over 10°C, and from 1950 to 2000, precipitation has gone down. A comparison of national forest surveys from two time periods (2009/2010 and 1981/1982) showed that forest cover dropped by 7% between 1981/1982 and 2009/2010 (Nget *et al.,* 2011). To better understand the country's climate change situation, it is important to keep an eye on deforestation activities in The Gambia and how they relate to climate change assessment. Since 1984, the expansion of agriculture has had a big effect on numerous agroecological zones in The Gambia's Central River Region (CRR). From 1984 to 2017, the amount of agriculture grew, whereas the amount of woodland savanna shrank. This change is largely due to clearing land for farming, which is affected by things like soil fertility loss, which makes it harder for plants to grow and makes CO_2 emissions worse. Farmers have indicated that the land is becoming less fertile, which means that crops are not growing as well as they used to. To keep up with agricultural production, they need to move into new areas. Changes in land use and soil degradation are linked to higher CO_2 emissions, which make climate change worse in the area (Sanneh et al., 2022). Researchers and stakeholders from all over the world are interested in the things that cause anthropogenic climate change, which are largely land-use practices (Goldewijk and Ramankutty, 2004; Song and Deng, 2017; Seddon et al., 2020; Temesgen *et al.,* 2021; Chen *et al.,* 2022). Despite growing concerns about environmental degradation and land resource management in The Gambia, there is a significant shortfall in comprehensive, long-term assessments of land use and land cover changes, particularly in the Central River Region and Upper River Region. Existing studies often focus on national or broader regional scales, with limited temporal coverage or outdated datasets that fail to capture recent trends and drivers of land transformation. As these regions are vital for agriculture, biodiversity, and rural livelihoods, understanding how land cover has evolved from 2002 to 2024 is crucial for informing sustainable land management strategies, climate adaptation planning, and policy interventions tailored to local contexts. It is equally important to compare how LULCC driven by agriculture and its related socio-economic development, such as settlement expansion, manifests in areas with marked ecological differences in climate and vegetation. This is because climate and vegetation characteristics are pull factors in agriculture and influence agricultural practices of farmers as well as the land’s ability to regain vegetation cover when a cultivated land is allowed to fallow, a practice common in the Gambia. This paper, therefore, seeks to compare the dynamics of LULCC in the CRR and URR, which are two agriculturally important but ecologically different regions in the Gambia.

3.3 Materials and Methods

The study was conducted in an extensive area along the floodplains of the river Gambia in CRR and URR, lying between Long. 15°27'43.905"W and 13°47'34.031"W, and Lat. 13°38'19.187"N and 13°26'52.939"N. The study area (Figure 1.1) cuts across two major agroecological zones of the country, namely, Sahel-Savannah Zone or Semi-Arid Zone and Sudano-Sahelian Zone or Riverine Zone. The Sahel-Savannah covers approximately 147,684 ha in the extreme north of the Central River Region. The soil suitability grouping for crops indicates 21% marginal, 36% unsuitable, and only 28% suitable (FAO, 1997). The zone is characterized by semi-agro-climate features such as limited surface water resources and lowlands with relatively low rainfall (below 900 mm). The unpredictable rainfall pattern makes rainfed crop production extremely difficult.

3.3.1 Land use and land cover classification

Five LULC categories were identified through field visits to align with the objectives of this study (Table 3.1). Landsat TM7, Landsat 8 and 9 (OLI) for the years 2002, 2013, and 2024 of the study areas were downloaded freely from the USGS portal (http://www.usgs.gov/website). Table 3.2 provides a detailed description of the images used in the study. Images of the dry season (November to March) were selected to ensure that cloud-free images were acquired.

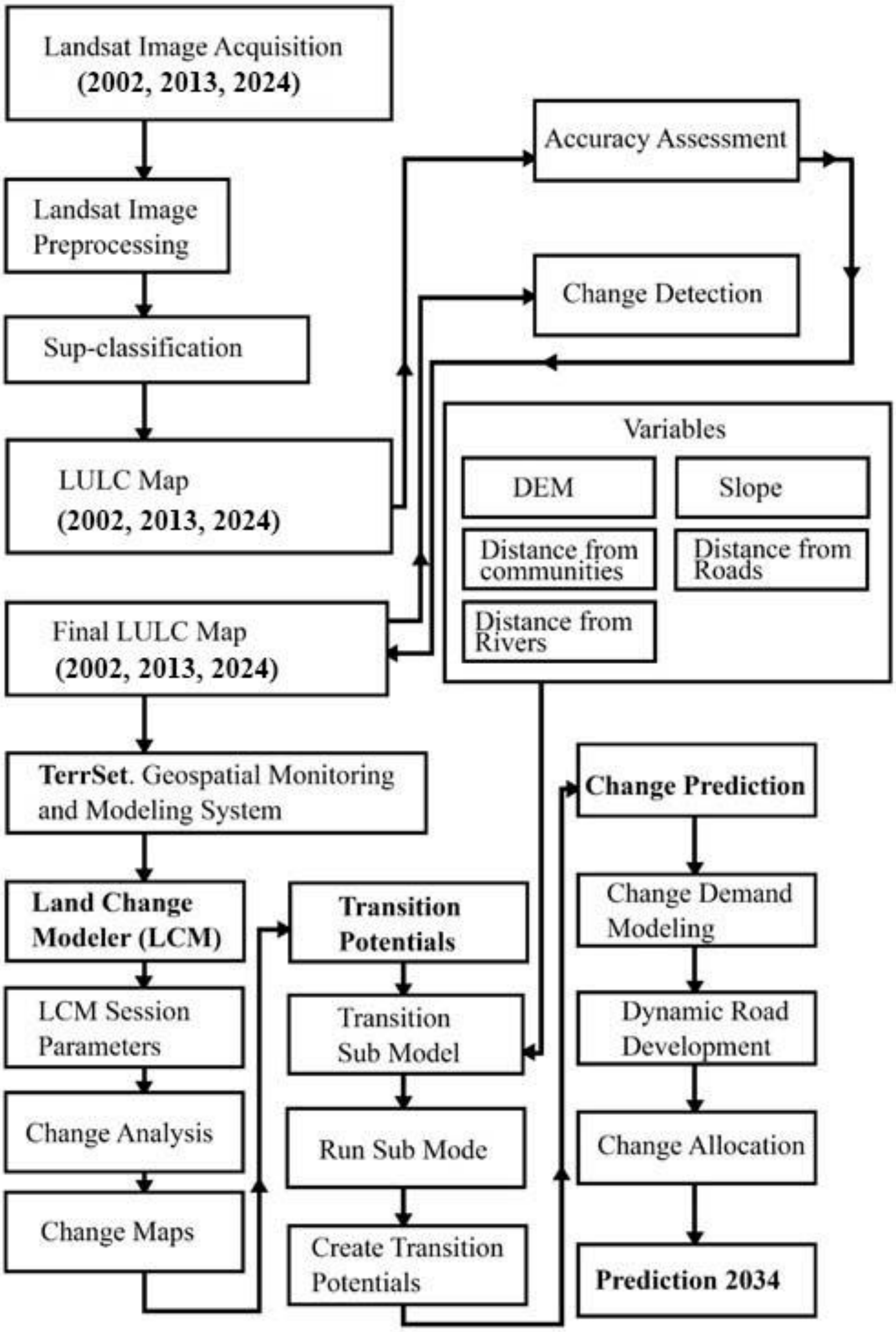

Figure 3.1: Methodology for LULC mapping and prediction

Table 3.1: Description of LULC classes for the study area. LULC classification is based on Dampha (2021)

No.	Classes	Descriptions
1	Waterbody	In the CRR and URR, waterbodies refer to rivers, lakes, reservoirs, or ponds used for both natural and economic activities.
2	Settlements	It includes houses and developed surfaces, such as industries, as well as bare grounds within communities.
3	Cropland	This includes areas used for the production of food crops, e.g., rice, maize, and sorghum.
4	Grassland	Land area that is covered by grasses predominantly *Andropogon gayanus, Hyparrhenia spp, Pennisetum pedicellatum (Kyasuwa), Sporobolus pyramidalis, Cenchrus biflorus* (FAO, 2010).
5	Forest	Land area with standing trees of a minimum height of 5m with a tree canopy cover of 15% and above.

A field GPS survey was undertaken to collect training and validation points of each identified land use/ land cover class in the study area. Forty-five training data points were collected for each LULC class described in Table 3.2

Table 3.2: Description of the images used in the study

Landsat name	Sensor	Path	Row	Spatial Resolution	Date
7	EMT+	203	51	30m	2002/04/04
7	EMT+	204	50	30m	2002/04/11
7	EMT+	204	51	30m	2002/04/11
8	OLI/TIRS	203	51	30m	2013/12/06
8	OLI/TIRS	204	51	30m	2013/12/13
9	OLI/TIRS	203	51	30m	2024/01/11
9	OLI/TIRS	204	51	30m	2024/01/18

3.3.2 Data Acquisition

Landsat satellite imagery was acquired for four historical time points - 2002, 2013, and 2024 - and used to simulate land cover changes and predict the 2034 land use and land cover (LULC) scenario for the CRR and URR in The Gambia. All images were downloaded from the USGS Earth Explorer platform and selected for minimal cloud cover and consistent seasonal conditions (dry season).

The satellite images were prepared by stacking the bands to form a multispectral image composite for each epoch. The images were classified using the Random Forest machine learning classifier and the field training datasets. The Random Forest classifier was chosen because it has been shown in the literature to yield higher classification accuracy than other classifiers in mapping highly heterogeneous landscapes (Nel *et al.*, 2022). All image processing and classification were performed in the R studio. The classification procedure yielded four LULC maps for the time steps 2002, 2013 and 2024.

3.3.3 Preprocessing of Satellite Imagery

Image preprocessing was conducted in Terrset and ArcGIS Pro 3.2, following standard procedures (Arfasa *et al.*, 2023). Radiometric Calibration and Atmospheric Correction using DOS (Dark Object Subtraction) method were used to reduce haze and scattering effects. Geometric correction was applied to ensure all images are aligned spatially using the UTM Zone 28N projection. Cloud masking was performed using the Fmask algorithm. Layer stacking was carried out for multispectral bands relevant for land cover classification.

3.3.4 Supervised Classification

Supervised classification was performed using the Maximum Likelihood Classification (MLC) algorithm, a widely accepted method for remote sensing LULC tasks (Seyam *et al.*, 2023). Classification was conducted for all three years: 2002, 2013, and 2024, into land use land cover classes: forest, grassland, cropland, settlements, and water bodies. Training samples were collected using a combination of historical Google Earth imagery, ground truth data from recent surveys, expert knowledge and high-resolution Sentinel-2 validation layers.

3.3.5 Accuracy Assessment

The accuracy of the LULC maps was assessed by generating error matrices for each using the field validation datasets as reference points. Overall, Users’, Producers', and Kappa accuracy were calculated from the error matrix to assess the accuracy of the classified maps. A change matrix was analyzed from 2002 to 2024 to assess the transitions. Accuracy assessment was conducted using confusion matrices for each classified map with the following metrics: Overall Accuracy (OA), Kappa Coefficient (k) Producers' and Users’ Accuracy (Nel *et al.*, 2022). Validation was performed using stratified random points compared to reference data from Google Earth and field observations.

3.3.6 LULC Change Detection (2002–2024)

Change detection was conducted using post-classification comparison, calculating area transitions, and generating change matrices between, 2002-2013-2024. These change matrices were generated using TerrSet’s Land Change Modeler (LCM), (Martín-Arias *et al.*, 2022), Eastman, highlighting patterns and conversion rates among land classes.

3.3.7 LULC Prediction for 2034

The Terrset Land Change Modeler (LCM) and CA-Markov Chain Model were used for the simulation of the 2034 LULC. Transition Potential Maps were generated using Multi-Layer Perceptron (MLP) neural networks, incorporating elevation, distance to roads, distance to rivers, distance to settlements and slope. Model calibration was done using data from 2002, 2013 and 2024. The Prediction Year was 2034. Validation was done by comparing the 2024 prediction (from 2002–2013 data) with the actual 2024 classified map for model reliability. This hybrid CA-Markov and neural network approach improves simulation accuracy by incorporating both spatial dependence and transition probability (Arfasa *et al.*, 2023).

3.4 Results and Discussion

3.4.1 Accuracy Assessment of LULC Classification at CRR

Water Bodies PA declined from 82.4% (2002) to 78.6% (2024). UA trend was maintained at 100% across all years. While the user’s accuracy indicates that all identified water bodies were correctly classified, the declining producer’s accuracy suggests the underestimation or misclassification of some water bodies, especially in 2013 and 2024. The fluctuations may reflect dynamic water levels or difficulties in distinguishing water bodies during certain years. Similar results have been obtained by Dampha (2021).

The Grassland PA trend remained high throughout, fluctuating slightly from 99.8% (2002) to 98.4% (2024). User Accuracy trend improved over time, rising from 96.6%

(2013) to 98.1% (2024). The Grassland was consistently well-identified, with only minor classification errors. The improvement in UA reflects fewer cases of other land covers (like croplands) being misidentified as grasslands. The Settlements PA trend recovered from 84.9% (2013) to 100% in 2024. Similar findings have been reported by Bah (2019). UA trend: Also improved, achieving 100% since 2013. Settlements initially faced some under classification in 2013, but subsequent maps corrected these issues, onward. This suggests better detection and mapping of urban areas, possibly due to improved satellite imagery or classification methods. Cropland's PA trend declined slightly from 100% (2002) and improved to 97.4% (2024). User Accuracy trend improved steadily from 94.4% (2002), before stabilizing at 95.5% (2024). Similar results have been obtained by Bah (2019).

The classification of croplands has become more reliable, despite minor fluctuations. The Forest Producer Accuracy trend: Maintained perfect 100% accuracy across all years. UA trend: Dropped from 88.2% (2002) to 77.8% (2013 and 2024), recovered to 100%. Similar findings have been reported by Tarawally *et al.*, (2019)

The Forest areas were correctly identified (high PA), but earlier years (2013) saw misclassification errors, with non-forest areas being labeled as forest (low UA). The 2024 recovery in UA suggests improved methods in distinguishing forests from other land covers, likely due to better spectral resolution or refined classification algorithms. Overall Accuracy and Kappa Statistics Overall accuracy: 2002: 99.3% 2013: 97.9% 2024: 97.5% Kappa statistics: 2002: 0.96 2013: 0.95 2024: 0.94. Similar results have been reported by Dampha, (2021b), who reported his kappa statistics were 0.63 and bush grassland was 86%, respectively. Its producer accuracy was from 1985 to 2020, during which it achieved the highest Producer's Accuracy (91%). Therefore, he was confident about the reliability of his classified map in terms of its ability to distinguish urban settlements from areas with green spaces.

Table 3.3: Summary of the classification accuracy for the Central River Region (CRR) land cover maps

LULC Class	2002		2013		2024	
	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)
Water bodies	82.4	100	74.7	100	78.6	100
Grassland	99.8	100	99.8	96.6	98.4	98.1
Settlements	100	95.4	84.9	100	100	100
Croplands	100	94.4	93.1	98.4	97.4	95.5
Forest	100	88.2	100	77.8	100	100
Overall accuracy	99.3		97.1		97.5	
Kappa	0.96		0.93		0.94	

3.4.2 Changes in LULC in CRR

The maps (Figure 3.2) highlight land use changes over time (2002, 2013 and 2024) in the CRR, with five land cover classes (water bodies, grassland, settlements, croplands, and forest) indicated in the legend. Grassland is dominant, covering a significant portion of the region but has decreased slightly compared to earlier years due to the spread of croplands and settlements. The forest has significantly reduced compared to its initial size in 2002. It now appears more fragmented and limited mainly to patches in certain areas. Cropland increased substantially, particularly near the center and southern part of the region. It now occupies areas previously classified as forest or grassland. Settlement expanded in 2024, especially in the central and eastern areas. Its presence is more widespread and clustered, indicating urban or village growth. Water bodies were consistent throughout all the years and follow the central river, which remains a prominent feature in the landscape. There has been a progressive expansion of croplands and settlements over the years, primarily at the expense of forests and grasslands. This indicates an increasing human activity, land conversion for agriculture, and urbanisation.

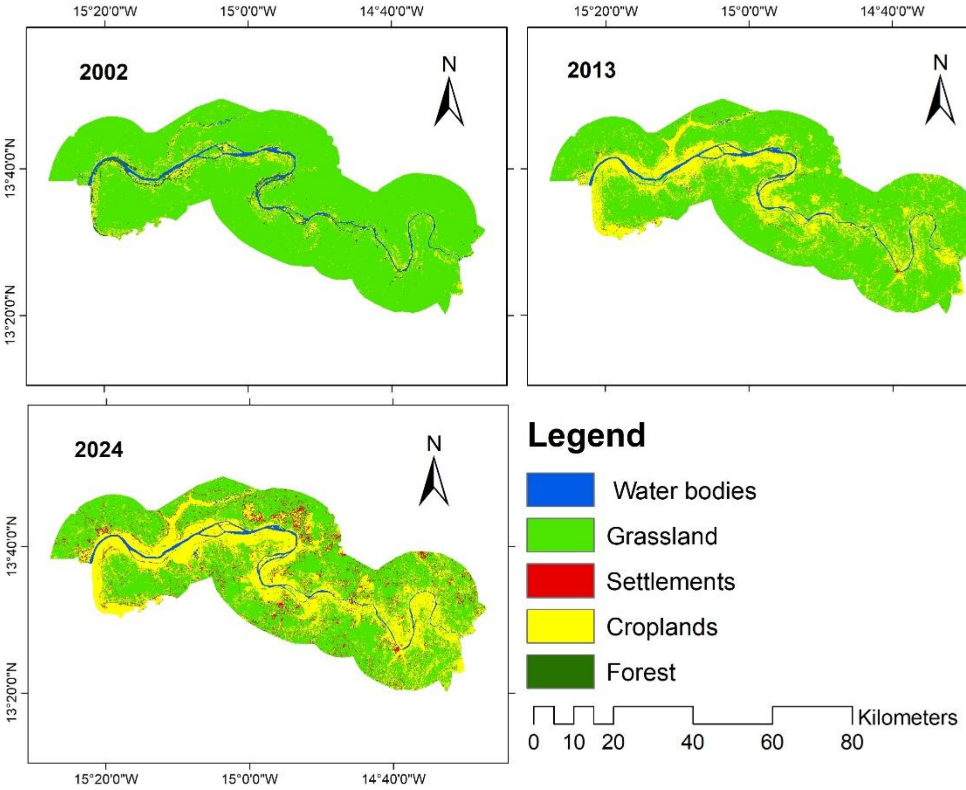

Figure 3.2: Land use and land cover maps of the Central River Region (CRR) for 2002, 2013, and 2024

Table 3.4 presents the LULC change matrix for the CRR between 2002 and 2013, and the results revealed significant shifts across five major land use classes in the research area. The croplands experienced the largest net gain (+53,698.86 ha), reflecting rapid expansion and encroachment into other land classes, especially savanna and forest, and the findings are similar to those reported by Seyam *et al*. (2023). However, the forest cover saw substantial deforestation, losing 5,881.77 ha, primarily to agriculture, whilst the water bodies experienced a net loss (-755.91 ha), which could be attributed to water extraction or natural changes, which agrees with the findings reported by Dampha (2021). The settlements expanded with a net gain of 1,611.18 ha, likely due to population growth and urbanization, but the grassland suffered a major net loss of 48,672.36 ha, mainly through conversion into cropland, and the results are similar to those obtained by Tarawally *et al.* (2019).

Table 3.4: LULC change matrix of Central River Region (CRR) showing the overall transition in land use classes directly from 2002 to 2013 (ha)

LULC Class	Water bodies	Grassland	Settlements	Croplands	Forest	Initial total	Gross loss	Net change
Water bodies	6874.20	397.44	12.96	669.69	0.18	7954.47	1080.27	-755.91
Grassland	216.63	212892.84	1484.73	49650.75	2.16	264247.11	51354.27	-48672.36
Settlements	0.00	80.10	32.85	20.79	0.00	133.74	100.89	1611.18
Croplands	97.74	1510.11	213.03	21823.11	128.16	23772.15	1949.04	53698.86
Forest	9.99	694.26	1.35	5306.67	467.1	6479.37	6012.27	-5881.77
Final total	7198.56	215574.75	1744.92	77471.01	597.6	302586.84		
Gross gain	324.36	2681.91	1712.07	55647.9	130.5			

The LULCC from 2013 to 2024 in the CRR was substantial (Table 3.5). Grassland, the dominant land cover in 2013, declined by 49,724 ha from 215,453 ha (71.24%) to 165,729 ha (54.8%), indicating widespread land conversion. In contrast, cropland expanded markedly, increasing by 33,349 ha, from 77,433 ha (25.6%) to 110,783 ha (36.63%), reflecting the intensification of agricultural activities in the region. The settlement area also saw a dramatic rise, growing from just 1,745 ha (0.58%) in 2013 to 18,632 ha (6.16%) in 2024, an increase of 16,887 ha, suggesting rapid urbanization and infrastructure development. Similar findings have been reported by Tarawally *et al.* (2019). Water bodies experienced a slight reduction of 226 ha, declining from 7,198 ha (2.38%) to 6,973 ha (2.31%), which may be linked to seasonal variability or changes in hydrological patterns. Meanwhile, forest areas continued to shrink, dropping from 598 ha (0.2%) to 310 ha (0.1%), a net loss of 287 ha, reflecting ongoing deforestation pressures, Bah (2019) reported similar findings. The deforestation pressures may stem from fuelwood harvesting or land clearing for agriculture and settlement expansion.

Overall, the data highlight a clear trend of natural land cover loss (grassland and forest) and conversion into anthropogenic uses (cropland and settlements). This transition raises concerns about biodiversity loss, soil degradation, and the need for sustainable land management in the CRR.

Table 3.5: Land use and land cover (LULC) change for the CRR of The Gambia from 2013 to 2024

Class	2013 (ha)	2024 (ha)	change (ha)	2013 (%)	2024 (%)	Change (%)
Water bodies	7198	6973	-226	2.38	2.31	-0.08
Grassland	215453	165729	-49724	71.24	54.80	-16.44
Settlement	1745	18632	16887	0.58	6.16	5.58
Cropland	77433	110783	33349	25.60	36.63	11.03
Forest	598	310	-287	0.20	0.10	-0.10

The transition matrix in Table 3.6 indicates significant land cover dynamics in the CRR over the 11 years. Waterbodies remained relatively stable, with 88.4% of their

2013 area persisting in 2024, while 9.0% transitioned into cropland, and 2.6% into settlements, suggesting some degree of wetland drainage or land reclamation for agriculture and urban development. Similar findings have been reported by Dampha (2021). Grassland, which initially occupied a large portion of the landscape, was notably unstable. Only 71.8% of its area remained grassland in 2024, while a substantial 22.2% of its area was converted into cropland, whilst 5.9% became settlements. Similar findings have been reported by Bah, (2019). This demonstrates that grasslands have been a primary source for agricultural expansion and urbanization, reflecting intense land conversion pressure. Settlement areas were relatively persistent, with 73.5% of the 2013 settlement area still classified as such in 2024. However, 15.8% reverted or transitioned to grassland, and 10.5% to cropland, possibly indicating classification changes or diminishing into surrounding vegetated areas. Similar findings have been obtained by Tarawally *et al.* (2019). Cropland was the most stable class, with 79.6% of its 2013 area remaining in the same category. However, 13.8% converted into grassland, and smaller proportions into settlement and waterbodies, suggesting some rotational land use or classification variability. Similar findings have been obtained by Bessah *et al.* (2019). In 2024, the forest exhibited significant instability, with just 25.4% of its area remaining wooded. Seventy-three point seven percent of forests has been converted into agricultural land, indicating significant deforestation, possibly due to the increasing frequency of agriculture. Merely 0.8% transitioned to settlement and grassland, underscoring the susceptibility of the forest ecosystems in the region. Climate change significantly impacts farmers in West Africa's agricultural industry. To offset reduced yields in their current fields, they must transfer their crops to areas with a greater concentration of trees (Serdeczny et al., 2017; Amjath-Babu et al., 2023).   This may elucidate the anomalous behaviors seen in this experiment. The matrix illustrates a significant transformation in land utilization, transitioning from grasslands and woods to increased agricultural and residential development. These achievements underscore the necessity of implementing tailored conservation and land management methods to safeguard land cover types essential for biodiversity and carbon sequestration.

Table 3.6: Transition matrix for CRR from 2013 to 2024 (ha)

Classes	Waterbodies	Grassland	Settlement	Cropland	Forest
Waterbodies	0.8839	0.0000	0.0257	0.0903	0.0000
Grassland	0.0008	0.7182	0.0589	0.2221	0.0000
Settlement	0.0020	0.1580	0.7350	0.1047	0.0003
Cropland	0.0057	0.1384	0.0578	0.7960	0.0020
Forest	0.0005	0.0000	0.0082	0.7373	0.2539

3.4.3 Accuracy Assessment of LULC Classification at URR

The classification of settlements remained perfect throughout the entire period, reflecting the precise mapping of built-up areas. This suggests that settlements are easily distinguishable from other land cover types, likely due to clear visual contrasts. Cropland’s PA varied throughout the years, improving from 93.2% (2013) to 97.4% (2024). The UA for cropland increased slightly from 94.7% (2002) to 95.5% (2024). Although croplands were consistently well-classified, some minor fluctuations in accuracy reflect the challenge of differentiating these areas from similar land cover types, such as forest or grassland. The forest’s PA remained 100% throughout all years, reflecting perfect detection of forested are Table 3.7 demonstrates that the accuracy of detecting aquatic goods was originally inadequate in 2013, but increased markedly and achieved perfection by 2024. This suggests that identifying water features has become more feasible in recent years, due to improvements in data resolution or developments in mapping techniques. The PA of the grassland shown minor fluctuations, reaching a maximum of 99.9% in 2013 and a minimum of 98.4% in 2024. User accuracy improved incrementally from 96.6% in 2013 to 99.1% in 2024. The Grassland was primarily well-categorized, although the PA had a little reduction by 2024. Recent alterations in UA demonstrate improved accuracy in classifying grasses, leading to a reduction in mistakes within the categorization of other land cover categories. The PA and UA of the settlement continuously achieved 100% each year. Dampha (2021) has demonstrated similar results. Its UA experienced fluctuations, declining to 77.8% in 2013 but recovering to 100% by 2024. Similar results have been observed by Bah (2019). While the UA for forests declined in 2013, improvements by 2024 indicate a more reliable classification. This fluctuation suggests possible confusion between forested areas and croplands during certain periods. The Overall

Accuracy and Kappa Coefficient Overall accuracy peaked at 99.5% in 2002 but decreased slightly to 98.2% by 2024. Kappa coefficient remained high, ranging from 0.94 to 0.98, indicating a strong agreement between the classification and ground truth data across all years. Similar results have been obtained by (Martín-Arias *et al.*, 2022).

Overall accuracy shows minor variations across the years, maintaining high values above 97%, reflecting the classification process's general reliability. The Kappa coefficient demonstrates that the land cover classifications were highly consistent, with only minimal misclassifications over time. The classification of land cover types in the URR has been consistently accurate, with overall accuracy above 97% and Kappa values near 1 across all years. By 2024, water features, communities, and woods have attained nearly flawless categorization, a finding corroborated by Mekonnen *et al.* (2018). Croplands and grasslands exhibited variances in accuracy, highlighting the intrinsic difficulties in differentiating between natural and anthropogenic environments. The advancements in classification accuracy over time indicate improvements in mapping methodologies and data integrity, facilitating enhanced land cover monitoring and management.

Table 3.7: Summary of the classification accuracy for the Upper River Region (URR) land cover maps

LULC Class	2002		2013		2024	
	PA (%)	UA (%)	PA (%)	UA (%)	PA (%)	UA (%)
Water bodies	92.7	100	74.8	100	100	100
Grassland	99.7	100	99.9	96.6	98.4	99.1
Settlements	100	100	100	100	100	100
Croplands	100	94.7	93.2	98.8	97.4	95.5
Forest	100	100	100	77.8	100	100
Overall accuracy	99.5		97.3		98.2	
Kappa	0.98		0.94		0.96	

3.4.4 Change in LULC in URR

In 2024, agriculture became the most common use of land. It grew a lot in the center and eastern parts of the country, which shows that farming has made a lot of progress (Figure 3.3). This was a big jump from 2002 and 2013. Grassland was still common in the area, especially in areas that weren't farmed much. But it lost its dominance in

2002 and became farmland or urban development in several places. Settlement grew a lot from 2002 to 2013, which shows that cities were growing and the population was growing. Along 2024, it grew more common and well-known, especially along water regions and along main roads. The forest was almost gone by 2013, and by 2024, it was no longer plainly visible, which meant that a lot of trees had been cut down. Forested regions have probably been turned into farmland or buildings in cities. Water bodies show the same pattern for the complete time period (all years). Aquatic ecosystems are small, yet they have a big effect on how people live and farm.   In 2002, the area was mostly made up of grassland, with just a few small settlements or farms.

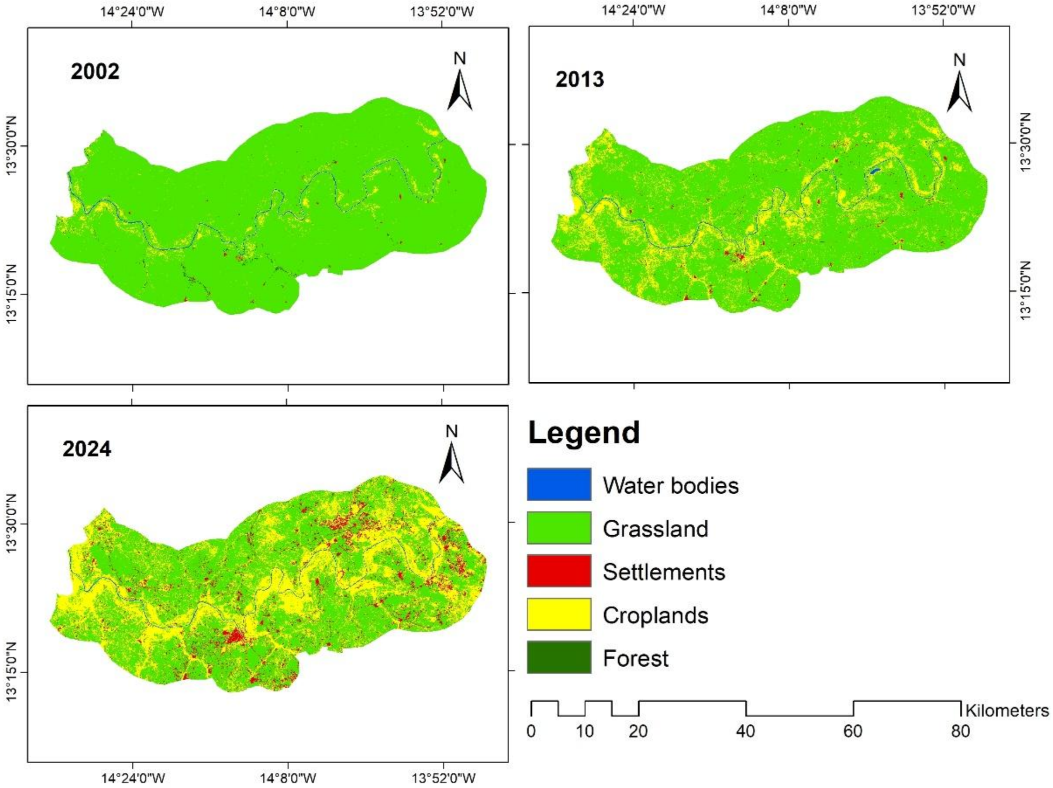

Figure 3.3: Land use and land cover maps of the URR for 2002, 2013, and 2024

Table 3.8 presents the LULC change matrix for the URR between 2002 and 2013, and the results reveal significant shifts across five major land use classes in the study area. Cropland recorded the highest net gain of 29,048.13 ha, increasing its total area from 8,128.17 ha in 2002 to 37,176.30 ha in 2013. The majority of this expansion came from grassland (29,214.54 ha) and forest (685.89 ha), findings are similar to those reported by Seyam *et al*. (2023) reflecting extensive agricultural encroachment into natural and semi-natural ecosystems. Similarly, settlements expanded by 1,447.29 ha, largely through the conversion of grassland (1,374.03 ha) and, to a lesser extent, cropland (145.35 ha) which agrees with the findings reported by Dampha (2021). Conversely, grassland experienced the most significant net loss of 29,895.93 ha, declining from 196,685.82 ha in 2002 to 166,789.89 ha in 2013. This loss underscores its role as the primary source for both agricultural and settlement expansion. Forest areas also declined sharply, losing 501.57 ha of their initial 852.75 ha, with the majority of losses attributed to conversion into cropland (685.89 ha)these results are similar to those obtained by Tarawally *et al.* (2019). Table 3.8 showed a slight net loss of 97.92 ha, primarily due to encroachment by grassland (151.74 ha) and cropland (83.70 ha).

Table 3.8: Land use and land cover change matrix of URR showing the overall transition in land use classes from 2002 to 2013 (ha)

LULC Class	Water bodies	Grassland	Settlements	Croplands	Forest	Initial total	Gross loss	Net change
			2002-2013 URR					
Water bodies	1431.90	151.74	0.00	83.70	0.00	1667.34	235.44	-97.92
Grassland	54.36	165952.44	1374.03	29214.54	90.45	196685.82	30733.38	-29895.93
Settlements	0.00	47.79	363.42	26.1	0.09	437.4	73.98	1447.29
Croplands	82.17	572.94	145.35	7166.07	161.64	8128.17	962.1	29048.13
Forest	0.99	64.98	1.89	685.89	99	852.75	753.75	-501.57
Final total	1569.42	166789.89	1884.69	37176.3	351.18	207771.48		
Gross gain	137.52	837.45	1521.27	30010.23	252.18			

Between 2013 and 2024, the URR underwent significant land use changes, primarily characterized by the reduction of natural vegetation and the expansion of anthropogenic land uses (Table 3.9). Grassland, which was the dominant land cover in 2013 at 166,596.75 ha (80.27%), experienced a substantial decline of 49,833.81 ha, reducing to 116,762.94 ha (56.26%) in 2024. Similar results have been obtained by (Tarawally *et al.*, 2019). This represents a significant 24% decrease, highlighting the scale of land conversion.

In contrast, cropland expanded dramatically over the same period, increasing by 37,638.72 ha from 37,155.96 hectares (17.9%) in 2013 to 74,794.68 ha (36%) in 2024. This sharp increase of 18.13 percentage points reflects intensifying agricultural activity, likely driven by growing food demands and rural livelihood pressures. Similar patterns of agricultural expansion at the expense of other land cover types have been reported in related studies Bah (2019). Settlement areas also grew substantially, rising from 1,882.35 ha (0.91%) in 2013 to 14,526.36 ha (7%) in 2024, an increase of 12,644 hectares. This 6% increase indicates rapid urbanization and infrastructure development in URR over the period. Comparable findings on settlement expansion and urban sprawl have been reported by Thenkabail (2015).

Meanwhile, water bodies decreased slightly by 225.54 ha falling from 1,569.24 ha (0.76%) to 1,343.70 ha (0.65%), likely due to hydrological shifts or encroachment. The most concerning change is observed in forest areas, which dropped from 351.18 ha (0.17%) to 127.80 ha (0.06%), a loss of 223.38 ha. This 0.11% decrease, though minuscule in percentage terms, indicates continued pressure on already limited forest resources. Similar results highlighting forest depletion due to pressure from human activities and land conversion have been reported by Dampha (2021). The LULCC trends in URR reveal a strong shift from natural vegetation, especially grassland and forest, toward cropland and settlements. These changes suggest increasing land use intensity, potentially at the expense of ecosystem services, biodiversity, and carbon storage. The findings underscore the urgent need for integrated land management strategies to balance development with ecological sustainability.

Table 3.9: Land use and land cover change at URR from 2013 to 2024

Class	2013 (ha)	2024 (ha)	Change (ha)	2013 (%)	2024 (%)	Change (%)
Water bodies	1569.24	1343.7	-225.54	0.76	0.65	-0.11
Grassland	166596.75	116762.94	-49833.81	80.27	56.26	-24.01
Settlement	1882.35	14526.36	12644.01	0.91	7.00	6.09
Cropland	37155.96	74794.68	37638.72	17.90	36.04	18.13
Forest	351.18	127.8	-223.38	0.17	0.06	-0.11

Water bodies remained relatively stable, with 72.2% of their 2013 area (about 1,133.6 ha) remaining unchanged (Table 3.10). However, 27.4% (about 429.1 ha) shifted to cropland, and a small fraction (0.4% or 6.2 ha) became settlement, suggesting water areas were converted primarily for agricultural use, aligning with findings by (Bessah *et al.*, 2019). Grassland, which had the largest area in 2013, showed considerable transition for a while, with 65.6% (about 109,359.9 ha) remaining grassland in 2024, 27.9% (roughly 46,462.2 ha) converted into cropland, which constitutes a major transformation. About 10,653.6 ha also transitioned into settlement, indicating grasslands are the primary source for both agriculture and urban expansion. Similar results have been obtained by Bah, (2019).

Settlements were quite stable, with 77.5% (about 1,459.3 ha) persisting, while 12.3% (about 230.9 ha) reverted to grassland and 10.3% (approximately 193.3 ha) transitioned to cropland. This may indicate some reclassification or expansion into adjacent land types. Cropland was also stable, with 73.7% (about 27,390.4 ha) remaining cropland. Notably, 19.3% (approximately 7,169.7 ha) of cropland in 2013 transitioned to grassland, and about 2,383 ha were lost to settlement. Interestingly, 2.3% (835.0 ha) turned into forest, suggesting some reforestation or classification change. Similar findings have been observed by Dampha (2021). Forest had the highest instability with only 10.6% (about 37.1 ha) remaining forest in 2024. A dominant 88.1% (around 309.4 ha) of the forest transitioned to cropland, indicating extensive deforestation. Small proportions also changed to grassland (4.2 ha) and settlement (0.4 ha). Similar findings have been observed by Ummah (2019).

The transition matrix clearly shows that the dominant trend in URR is the conversion of grassland and forest into cropland and settlements. The largest single transition is grassland to cropland, contributing over 46,000 hectares to cropland expansion. Similar findings have been reported by Bah (2019). Forest areas were almost entirely lost to agriculture, with only 10.6% remaining. These patterns raise serious concerns about ecological degradation, loss of biodiversity, and diminishing carbon sinks and point to the need for sustainable land use policies.

Table 3.10: Transition matrix LULC 2013 to 2024 for URR (ha)

		Transition Matrix			
Class	Water bodies	Grassland	Settlement	Cropland	Forest
Water bodies	0.7223	0.0000	0.0040	0.2736	0.0002
Grassland	0.0006	0.6564	0.0640	0.2790	0.0000
Settlement	0.0000	0.1226	0.7748	0.1026	0.0000
Cropland	0.0031	0.1930	0.0646	0.7370	0.0225
Forest	0.0000	0.0120	0.0010	0.8813	0.1056

3.4.5 Future LULC Change Prediction for CRR and URR

The predicted LULCC from 2024 to 2034 at CRR indicates a continuation of urbanization and agricultural expansion at the expense of natural ecosystems such as grasslands and forests. Agriculture will remain the primary driver of land transformation, with grassland areas being the most affected. The decline in forest cover raises concerns about environmental sustainability and biodiversity loss, while the shrinking of water bodies highlights potential water resource challenges. These trends suggest a need for integrated land-use planning to balance development and conservation efforts in the coming decade.

Table 3.11 shows the overall transition in land use classes directly from 2024 to 2034. Water bodies and forest areas will experience further decline, though water bodies will shrink more slowly than in previous years. Grasslands will see the largest net loss (37,211.85 ha), continuing its transformation into agriculture and settlements. The Settlements will expand substantially, with a forecasted increase of 5,379.57 ha, driven primarily by the conversion of grasslands. Cropland is projected to increase by 32,090.13 ha, reinforcing agriculture as a dominant land use in the region. Forest cover will face significant losses, with over 50% of the existing forest expected to disappear by 2034

Table 3.11: Predicted LULC change matrix of CRR showing the overall transition in land use classes directly from 2024 to 2034 (ha)

LULC Class	Water bodies	Grassland	Settlements	Croplands	Forest	Initial total	Gross loss	Net change
Water bodies	6662.43	0.27	0.00	315.18	0.00	6977.88	315.45	-90.72
Grassland	0.72	128310.66	5407.83	32067.18	0.00	165786.40	37475.70	-37211.85
Settlements	0.00	24.48	18597.96	16.47	0.00	18638.91	40.95	5379.57
Croplands	224.01	239.13	12.69	110368.17	28.89	110872.89	504.72	32090.13
Forest	0.00	0.00	0.00	196.02	114.75	310.77	196.02	-167.13
Final total	6887.16	128574.54	24018.48	142963.02	143.64	302586.84		
Gross gain	224.73	263.88	5420.52	32594.85	28.89			

Table 3.12 provides a forecast of LULCC in the URR between 2024 and 2034, showing the transitions between five (5) LULC classes: water bodies, grasslands, settlements, cropland, and forest. It details the initial total area of each class, the amount of gross loss, and the net change over the prediction period. Water bodies are predicted to grow slightly, adding 219 ha, despite some minor conversions (2.43 ha) to cropland. This suggests an expansion of water features, potentially from increased rainfall, improved water management, or flooding. Grassland will experience significant losses, primarily to settlements (6,247.26 ha) and croplands (14,176.53 ha).

Settlements are projected to expand substantially, gaining 6,266 ha, primarily from grasslands and croplands. This reflects an ongoing urbanization and population growth. The minimal loss of 17 ha indicates that once areas are developed, they are unlikely to revert to other land cover types. Croplands will expand significantly, gaining over 14,286 ha, mostly from grassland areas. This highlights the growing pressure for agricultural production, likely due to increased food demands or agricultural intensification. However, small areas are expected to transition to other land covers, including water bodies (221 ha), suggesting land-use diversification. Forest cover will continue to decline, with almost 80% of the existing forest area projected to be converted into agricultural land. Only 2.88 ha are expected to regenerate as forest, underscoring the challenge of forest conservation amid agricultural expansion.

The highest gains in LULC will be made by cropland (+14,286 ha) and settlements (+6,266 ha), whilst the highest losses will occur in grassland (-19,931 ha) and forest (-100 ha). The data suggests that cropland expansion and urbanization will dominate LULCC trends over the next decade. While some minor gains are predicted for water bodies, forest cover continues to shrink, highlighting the region's vulnerability to deforestation. The loss of the grassland also reflects a shift towards more intensive land use. Similar findings have been obtained by (Martín-Arias *et al.*, 2022). The URR is predicted to undergo significant land cover transformation between 2024 and 2034, driven primarily by agricultural expansion and urban development. While settlement and cropland are expected to grow, this comes at the cost of grassland ecosystems and forest areas, potentially leading to ecological degradation. If these trends continue, sustainable land management practices will be necessary to balance development with environmental conservation.

Table 3.12: Predicted LULC change matrix of URR showing the overall transition in land use classes directly from 2024 to 2034 (ha)

LULC Class	Water bodies	Grassland	Settlements	Croplands	Forest	Initial total	Gross loss	Net change
Water bodies	1343.07	0.00	0.00	2.43	0.00	1345.5	2.43	218.97
Grassland	0.18	96491.97	6247.26	14176.53	0.00	116915.94	20423.97	-19930.95
Settlements	0.00	12.33	14514.48	4.68	0.00	14531.49	17.01	6249.15
Croplands	221.22	480.69	18.9	74127.06	2.88	74850.75	723.69	13562.91
Forest	0.00	0.00	0.00	102.96	24.84	127.8	102.96	-100.08
Final total	1564.47	96984.99	20780.64	88413.66	27.72	207771.48		
Gross gain	221.40	493.02	6266.16	14286.60	2.88			

Figure 3.4 shows the maps for the projected LULC distribution in the CRR and URR of The Gambia for the year 2034. The maps provide a spatial visualization of five land cover categories: water bodies, grassland, settlements, croplands, and forest. Croplands dominate both CRR and URR landscapes, especially along the river and throughout central zones. This widespread expansion of croplands is consistent with findings from previous LULC analyses, which indicate a steady increase in agricultural land at the expense of natural vegetation. In CRR, cropland occupies a central belt running from east to west. In URR, cropland is scattered more diffusely but is still prominent. This trend reflects intensified agricultural activities likely driven by population growth and food security demands. Grassland is still present but noticeably fragmented and reduced, particularly in central and northern parts of both regions. The reduction is more pronounced in CRR, indicating conversion to either cropland or settlements. Grassland loss may negatively impact biodiversity and pastoral livelihoods. Settlements have visibly increased in density and spread, especially near river corridors and road networks.

CRR shows clusters of red patches near central water routes but URR displays a more scattered yet extensive pattern of settlements, suggesting urban sprawl. The growth of settlements aligns with urbanization trends reported in national demographic surveys (Schreuder, 2014; Usinyo *et al.*, 2022), indicating pressure on land resources and infrastructure. Forest areas appear marginally and scattered, particularly in CRR. In URR, forests are slightly more continuous in the eastern parts. The limited forest extent indicates ongoing deforestation and fragmentation, consistent with carbon stock losses noted in recent studies. Forest degradation contributes to reduced carbon sequestration and threatens forest-dependent livelihoods. The maps show rivers and water bodies primarily in central corridors. These are important for irrigation and settlement patterns but remain relatively unchanged in spatial extent. Water availability continues to be a critical driver for land use decisions in these regions.

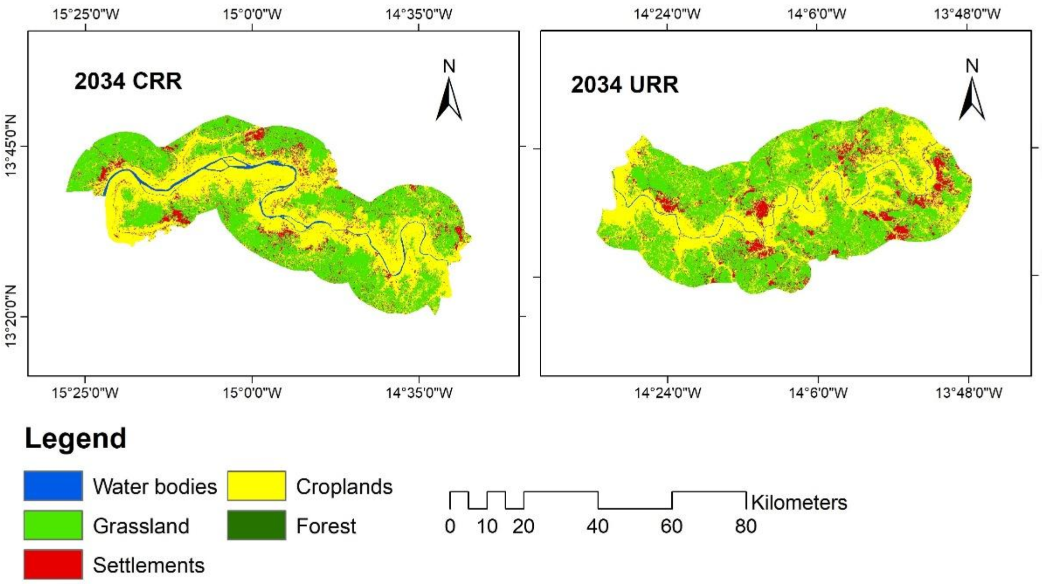

Figure 3.4: Predicted Land use and land cover maps of the CRR and URR for 2034

3.5 Conclusions and Recommendations

3.5.1 Conclusions

Significant shifts in LULC types observed in the study (2002-2024). Forest cover in CRR declined significantly, to just 310 ha, representing a (95.2%) loss. Forest cover in URR fell to just 127.8 ha by 2024, a loss of 85%. Grasslands, in CRR, declined to 165,729 ha by 2024, an overall loss of 37.3%. In URR, it decreased to 116,763 ha, which represents a 40.6% reduction, highlighting the intensity of land clearing for agricultural purposes. Croplands in CRR increased to 110,783 ha by 100%. In URR by 74,794.68 ha, marking a 82%. Settlement areas in CRR increased to 18,632ha by 100%. This represents rapid rural population growth in URR, by 14,526.36 ha in 2024, an increase of over 100%. This dramatic urban growth reflects increased rural-to-urban migration and infrastructure development. Water bodies in CRR saw a moderate reduction over the period by 6,973 ha equating to a 12.3% loss. In URR also experienced notable shrinkage, decreasing by 19.4% to 1,343.7 ha. This reduction may be attributed to seasonal variability, upstream damming, and increased irrigation demands. These declines in natural land cover classes have serious implications for biodiversity.

Significant shifts in LULC types observed in the study (2024-2034). Cropland experienced the highest net gain: 32,090.13ha (28.94%), in CRR and 13,562.91ha (18.12%) in URR, primarily from conversions from grassland and other land use types. Settlements also expanded, gaining 5,379.57ha (28.86%) in CRR and 6,249.15 ha (42.97%) in URR. Conversely, grassland saw the largest net loss of 37,211.85 ha (-22.45%) in CRR and 19,930.95 ha (-17.04%) in URR, indicating substantial transformation into cropland and settlements. Water bodies and forests both experienced slight reductions, with net losses of 90.72ha (-1.30%) and 167.13 ha (-53.77%), respectively. These trends highlight increased human activities, particularly agricultural expansion and urbanization, leading to notable landscape transitions over the decade. Water bodies and forests have also declined by 2018.97 ha (16.28 %) and -100.08ha (-78.31%) respectively.

3.5.2 Recommendations

Policy Recommendation

The Ministry of Agriculture in the Gambia should promote the adoption of sustainable agricultural practices, such as agroforestry, crop rotation, and conservation agriculture, to reduce agricultural expansion into forests and grasslands while maintaining productivity. The Forestry Department should also implement policies to protect remaining forest and grassland areas from further conversion and promote restoration and agroforestry practices to improve tree cover.

Research Recommendation

Research institutions should establish monitoring and early warning systems to track land-use changes. This will help policymakers respond promptly to undesirable trends, such as forest loss or excessive agricultural encroachment. By combining satellite remote sensing with ground-based surveys to monitor land-use changes, and integrating these data with predictive models, we can better anticipate future trends. Early warning dashboards with clear thresholds can alert policymakers to issues such as forest loss or agricultural encroachment. Training local stakeholders and maintaining direct communication with decision-makers ensures timely and effective responses

CHAPTER 4 TREE-BASED CARBON STOCK DYNAMICS IN THE CENTRAL RIVER REGION AND UPPER REGION OF THE GAMBIA

4.1 Abstract

The dynamics of tree-based carbon stocks are crucial for climate mitigation, especially in developing countries undergoing rapid land use changes. This study quantifies carbon stock fluctuations across four land use categories: forest, grassland, cropland, and settlement in The Gambia's Central River Region (CRR) and Upper River Region (URR) from 2002 to 2024, with projections extending to 2034 using the InVEST carbon storage and sequestration model. Land cover maps from 2002, 2013, and 2024 were employed in conjunction with class-specific carbon pool data to evaluate changes in aboveground carbon. The results revealed a decline in total carbon stock from 14,259,109.79 Mg in 2002 to 11,960,695.2 Mg in 2024, representing a fall of 2,298,414.59 Mg (16.1%) over 22 years. Forests, the primary category for carbon storage, had a substantial reduction, diminishing from 9,386,484.44 Mg in 2002 to 4,797,735.2 Mg in 2024. Grasslands fell from 1,089,660.41 Mg to 849,988.7 Mg. In contrast, agricultural and urban regions have increased in size but have much less carbon storage capacity, contributing minimally to total stocks. The projection for 2034 indicates further declines, with forest carbon expected to decline to 4,202,738.9 Mg and total carbon stock decreasing to 11,317,586.02 Mg. These reductions are closely associated with land conversion for agricultural and infrastructure objectives. This study highlights the urgent need for sustainable land use planning, reforestation, and carbon-focused conservation to protect The Gambia's natural integrity and improve climate resilience.

4.2 Introduction

Tree-based ecosystems are essential for carbon cycling in terrestrial settings, acting as significant carbon sinks and regulators of atmospheric carbon dioxide (CO_2) concentrations. Trees facilitate carbon sequestration by accumulating biomass both aboveground (stems, branches, leaves) and belowground (roots), while simultaneously enhancing soil organic matter through litterfall and root turnover. These activities directly influence soil organic carbon (SOC) stores, which constitute an essential element of the global carbon reservoir (Kola-Mustapha et al., 2023). Trees affect the buildup of soil organic carbon through many mechanisms. They initially provide significant organic matter to soils through litterfall (leaves, branches, and fruit) and the decomposition of root biomass. These inputs supply substrates for soil microbial populations, facilitating the development of stable soil organic carbon molecules. Established tree species prevalent in dry areas facilitate the transport of carbon into deeper soil layers, hence improving the vertical distribution of soil organic carbon (SOC) and augmenting its long-term stability.

Secondly, tree canopies alter the subsurface environment, affecting soil temperature and moisture levels. Soils under tree cover often demonstrate reduced temperatures and heightened moisture retention relative to uncovered soils, hence decelerating organic matter decomposition and promoting carbon sequestration (Seddon et al., 2020). Trees safeguard soils from erosion by reinforcing soil structure with their roots, so averting SOC loss due to surface flow. The species, density, and age of tree stands substantially influence the extent of these contributions. Natural forests often possess more soil organic carbon stores than plantations or degraded woods, due to enhanced biomass production and ongoing organic contributions. (Aabeyir *et al.*, 2020). Agroforestry systems, which combine trees with crops or animals, can augment soil organic carbon (SOC) by preserving perennial plant cover and fostering different root architectures. Temperature affects both tree metabolic processes and soil microbial activity. Increased temperatures can enhance tree development to some extent; but, they may also hasten the breakdown of organic matter, therefore diminishing soil organic carbon stocks if decomposition rates exceed carbon inputs (Gebeyehu *et al.*, 2020). Conversely, increasing precipitation often promotes tree development, resulting in greater litterfall and root biomass, which in turn aids in the storage of soil organic carbon (Hu *et al.*, 2016). Climate variability, characterized by heightened occurrences of droughts or extreme weather events, can impose stress on tree populations, diminish biomass output, and thus restrict organic inputs to the soil. Villamor *et al.* (2017) discovered that climate-induced alterations in plant cover might trigger cascade impacts on soil carbon dynamics, underscoring the necessity of including climatic considerations into carbon stock evaluations. Alterations in land use, notably deforestation and agricultural proliferation, significantly affect carbon sequestration in trees. Deforestation for agricultural or residential purposes significantly diminishes aboveground biomass carbon and disrupts the constant addition of organic matter to soils, resulting in a decrease in soil organic carbon. In West Africa, conventional agricultural methods, including slash-and-burn agriculture, timber extraction for fuel, and shifting cultivation, have traditionally resulted in the deterioration of tree cover. These activities reduce aboveground carbon stores and destabilize soil organic carbon by exposing soils to erosion and accelerating decomposition rates. Conversely, tree-based strategies such as afforestation, replanting, and agroforestry provide avenues for the rehabilitation of carbon reserves. The integration of trees into agricultural landscapes via agroforestry systems markedly enhances soil organic carbon (SOC) levels, especially with the inclusion of deep-rooted, nitrogen-fixing species (Haynes and Yongfu, 2014). Managed woodlots and forest restoration initiatives can augment carbon sequestration in both aboveground and belowground ecosystems. Comprehending the geographical scope and dynamics of tree-based land use is essential for forecasting soil organic carbon trends and formulating appropriate carbon management strategies in the sub-region. In The Gambia's Central River Region (CRR) and Upper River Region (URR), tree-based land use and land cover systems, including natural forests, agroforestry areas, and cultivated woods, have traditionally facilitated substantial carbon sequestration. Nonetheless, pressures from agricultural growth, changes in land use practices, and climate unpredictability are altering the structure and function of these ecosystems, significantly affecting carbon cycles. Comprehending the impact of alterations in tree-based land cover on carbon stocks is crucial for improving carbon sequestration and bolstering ecosystem resilience to climate change (Dampha, 2021). This study examines the dynamics of tree-based carbon stocks in CRR and URR, highlighting the relationships among plant cover, soil characteristics, and climatic conditions. Climatic variables, including temperature and precipitation, significantly influence tree growth, biomass generation, and, consequently, the mechanisms of carbon sequestration in trees. In the CRR and URR, precipitation patterns exhibit significant periodicity, characterized by a pronounced wet season that fosters vegetative growth and organic matter accumulation. (Tahmasebi *et al.*, 2020). Employing a geostatistical modeling technique, we want to forecast present and future carbon stock distributions associated with tree cover, thereby facilitating informed land management and climate mitigation initiatives (Bah, 2019). To evaluate the dynamics of tree-based carbon stocks in the CRR and URR, I apply geostatistical modeling approaches that incorporate tree-based biomass as input (Cavus and Yazici, 2021). Predictive models offer scenario assessments, including forecasts of future carbon stocks under various land use and climate change scenarios. These techniques are essential for directing reforestation initiatives, establishing sustainable agroforestry systems, and prioritizing conservation activities in regions with the greatest potential for carbon sequestration (Villamor *et al.,* 2019). Augmenting tree-based carbon stores is a strategic approach for alleviating climate change, conserving biodiversity, and enhancing livelihoods in The Gambia. Augmenting tree cover by reforestation, agroforestry, and sustainable forest management can concurrently elevate aboveground biomass carbon and improve soil organic carbon reserves, producing beneficial outcomes for both environmental and socioeconomic goals (Kola-Mustapha et al., 2023). Policymakers and land managers might utilize spatial evaluations of arboreal carbon reserves to identify locations for tree planting projects, carbon offset initiatives, or land restoration efforts. Incorporating tree-based carbon strategies into national development plans would enable The Gambia to fulfill its Nationally Determined Contributions (NDCs) under the Paris Agreement while enhancing resilience to climate hazards. (Dampha, 2021). A thorough comprehension of tree-based carbon stock dynamics is crucial for developing sustainable land use systems that harmonize productivity, environmental integrity, and carbon sequestration (Kola-Mustapha *et al.*, 2023).

4.3 Materials and Methods

4.3.1 Tree Inventory

Four land use classes (forest, grassland, cropland, and settlement) were considered for the tree inventory. From a prepared grid map, 20 sampling points were randomly chosen for each of the four LULC types in each region and the GPS coordinates were loaded onto a GPS set indicating the centre of the plots. In the field, the sampling points were located using GPS based on the identified coordinates on the map. At each sampling point, a circular plot with a radius of 26m was laid, resulting in a plot size of approximately 2124 m^2. On each plot, the DBH of trees with diameters above 10cm were measured with a diameter tape and the height of the trees were measured with a Sunnto clinometer. Data was recorded on field data sheets and then entered manually into spreadsheets. Errors were reduced through spot checks of the entered data.

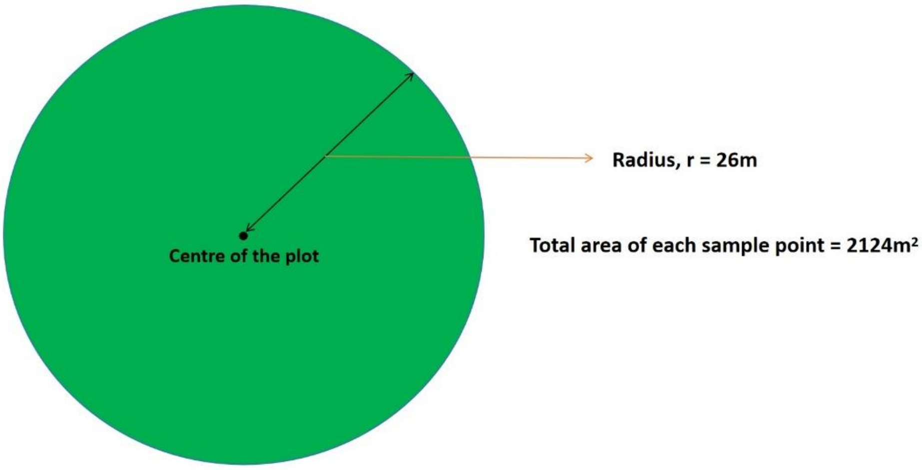

Figure 4.1: Illustration of a sample plot for the tree inventory.

4.3.2 Estimation of the Aboveground Carbon from Forest Inventory

The aboveground biomass (ABG) was estimated from the tree measurements using Chave Equation 1 (Chave *et al.*, 2014). The wood density of each tree was extracted from the global database (Chave *et al.*, 2005).

$$AGB = 0.0673 \times (WSG \times DBH^2 \times \mathrm{H})^{0.976} \quad (1)$$

Where AGB is the aboveground biomass (kg) at the tree scale, WSG is the tree wood density (g cm^{-3}), the DBH is the diameter at breast height (cm), and H is the tree height (m). After calculating the AGB in each plot, the sum was calculated and converted to megagram per/hectare. Statistical analyses were done using Chi-square goodness of fit and Student's t test to determine differences in tree populations and above-ground biomass between CRR and URR. The carbon loss or gain was estimated as the difference between the carbon stock of the previous LULC and the present one at a given location.

The Integrated Valuation and Ecosystem Services and Tradeoffs (InVEST) carbon model Imran *et al.* (2022) was used to estimate carbon stocks in the CRR and URR landscape. InVEST requires categorical land cover maps and carbon values for each land cover class in the study landscape. This study used the above-ground carbon (AGC) values (MgC/ha) for various LULC classes. The AGC for the classes in the landscape was sourced from the field inventory data. Values of 0.38 and 0.32 were used for forest in URR and CRR, respectively. Corresponding values for grassland were 0.1 for URR and 0.08 for CRR. For the cropland, 0.07 for URR and 0.06 for CRR were used. Settlement values were 0.37 for URR and 0.09 for CRR. AGC value for the water body was set to zero.

4.4 Results and Discussion

4.4.1 Distribution of trees in the various LULC classes in CRR and URR

The analysis of tree distribution across different LULC categories reveals notable differences between the CRR and URR (Table 4.1). Species presence and abundance vary by region and LULC type, suggesting differences in ecological conditions, land management practices, and levels of anthropogenic disturbance. The number of trees in the forest were higher in the URR (134 total all species) than in the CRR (57 total, all species), equivalent to tree density of 32 trees /ha and 13 trees /ha for the URR and CRR, respectively (X^2 = 31.04, df =1, p <0.05). A similar observation was made in the settlements where 48 trees were found in the URR as against only 3 in the CRR (X^2=39.71, df=1, p<0.05). In the grassland and cropland, however, there were no significant differences in the number of trees between CRR and URR. The recorded numbers were 37 and 23 for grassland and 40 and 26 for cropland (Table 3.1) with p values of 0.07 and 0.084, respectively.

Combretum glutinosum was the most abundant species in both regions, with a higher occurrence in URR (53) than in CRR. (19). Additionally, species such as *Cassia sieberiana*, *Guiera senegalensis*, *Azadirachta indica*, and *Adansonia digitata* were found exclusively in URR forests, indicating richer species diversity and potentially better ecological integrity. This could be attributed to more effective forest conservation practices or lesser anthropogenic interference in the URR. Similar findings have been obtained by (Kucuker *et al.*, 2015). In contrast, CRR forests were dominated by fewer species, such as *Combretum micranthum* (13) and *Terminalia macroptera* (5), which indicates lower diversity and possibly more disturbed forest environments due to human activities like logging or shifting cultivation. Comparable results have been reported by Kucuker *et al.* (2015). Conversely, CRR forests exhibited dominance by a limited number of species, notably *Combretum micranthum* (13) and *Terminalia macroptera* (5), suggesting less variety and perhaps more disturbed forest ecosystems attributable to anthropogenic activities such as logging or shifting agriculture. Comparable findings have been documented by Aabeyir *et al.* (2020). Grasslands in CRR exhibited a greater abundance of woody species compared to those in URR. *Combretum micranthum* and *Combretum glutinosum* were prevalent in CRR grasslands, indicating a potential shift to forested savannas or the natural recovery of degraded forests. In contrast, URR grasslands exhibited no woody vegetation, with *Combretum glutinosum* (11) and *Vitex trifolia* (12) as the sole notable species. This may result from heavy livestock grazing or recurrent bushfires that inhibit the regrowth of woody species in URR. The occurrence of tree species in croplands, including *Combretum micranthum* (24), *Lannea acida* (5), and *Combretum glutinosum* (7), which are prevalent in CRR, indicates a propensity for agroforestry methods or spontaneous regeneration on fallow areas. In URR croplands, the sparse presence of trees indicates more intense farming techniques and land removal that diminish the prevalence of woody species. The proportion of tree species in settlement areas varied significantly between the two regions. URR communities had a significantly greater quantity of trees, notably Mangifera indica (12), *Combretum micranthum* (23), and *Vitex simplicifolia* (11), suggesting deliberate cultivation for sustenance, shade, or aesthetic purposes. Conversely, CRR towns had little vegetation, including only sporadic occurrences of species such as *Combretum micranthum* and *Vitex simplicifolia*. This suggests less tree planting or higher population pressure in CRR settlements, which may inhibit the presence of woody plants. While not significant at the 0.05 level, the result is close to statistical significance ($p = 0.083$), suggesting that URR may host a higher number of individual trees per species in settlement areas compared to CRR. This aligns with earlier results showing higher above-ground biomass in URR settlements.

The URR has a notably higher number of trees in forest and settlement areas, while CRR leads in cropland and grassland. Similar results have been obtained by (Bessah *et al.*, 2019). The differences in species richness and distribution between CRR and URR reflect variations in climatic conditions, land use intensity, and human management practices. URR, having slightly more rainfall and perhaps better-preserved forests, supports greater tree diversity, particularly in forested and residential areas. In addition, URR has benefited from tree planting project sponsored by UNEP, in the past (UNEP, 2015) and this may explain why tree stocks in the settlement far exceed in CRR, on the other hand, shows signs of intermediate disturbance, with more woody species in grasslands and croplands, possibly due to traditional agroforestry practices or land abandonment. Moreover, the high presence of tree species in URR settlements suggests greater integration of trees into urban or peri-urban landscapes, likely due to socio-economic factors such as the use of trees for food, medicine, or cultural practices.

Table 4.1: Species distribution (number of trees/sp.) across various LULC types in the CRR and URR

Data is from 20 plots with an area summing up to approximately 4.24 ha for each LULC in each region

	Forest		Grassland		Cropland		Settlement	
Species	CRR	URR	CRR	URR	CRR	URR	CRR	URR
Acacia macrotachys	4	11	3	0	0	0	0	0
Acacia seyal	1	0	0	0	0	0	0	0
Bombax costatum	1	0	0	0	0	0	0	0
Combretum glutinosum	19	53	13	11	7	2	0	0
Combretum micranthum	13	1	11	0	24	17	2	23
Combretum nigerican	2	2	1	0	2	0	0	0
Cordyla africana	1	5	0	0	0	0	0	0
Lannea acida	3	3	3	0	5	4	0	0
Pistigama thonningii	1	0	1	0	0	0	0	0
Prosopis africana	1	0	1	0	0	0	0	0
Strychnus spinosa	1	5	0	0	0	0	0	0
Terminalia macroptera	5	0	2	0	0	0	0	0
Vitex simpilicitiforlia	3	8	2	0	2	1	1	11
Ziziphus mauritania	2	0	0	0	0	0	0	0
Adansonia digitata	0	1	0	0	0	0	0	0
Azadirachata indica	0	2	0	0	0	0	0	2
Cassia sieberiana	0	12	0	0	0	0	0	0
Guiera senegalensis	0	4	0	0	0	0	0	0
Heeria insignis	0	1	0	0	0	0	0	0
Mangifera indica	0	1	0	0	0	0	0	12

Pterocarpus erinaceous	0	1	0	0	0	0	0	0
Sclerocarya birrea	0	1	0	0	0	0	0	0
Terminalia glaucescence	0	1	0	0	0	0	0	0
Vitex trifolia	0	22	0	12	0	2	0	0
Total Number of trees	**57**	**134**	**37**	**23**	**40**	**26**	**3**	**48**

Table 4.2 presents a detailed inventory of tree species observed across different LULC types: forest, grassland, cropland, and settlements in the CRR and URR of The Gambia. It includes the average DBH and average height for each species, which are critical metrics for estimating above-ground biomass and, by extension, carbon stocks. The species dissemination and structural characteristics offer insights into vegetation composition, ecosystem maturity, and land management practices. Forest areas in both CRR and URR show the greatest structural variation among tree species. Notably, species such as *Bombax costatum* (DBH: 74 cm, CRR), *Prosopis africana* (DBH: 76 cm, CRR), and *Terminalia macroptera* (DBH: 68.2 cm, CRR) indicate mature, carbon-rich forest stands, especially in CRR. Meanwhile, URR forests are characterized by tall species such as *Cordyla africana* (Height: 7.3 m), *Adansonia digitata* (Height: 14 m, DBH: 109 cm), and *Pterocarpus erinaceus* (DBH: 126 cm), suggesting old-growth or well-conserved forest patches.

The high average DBH and tree height in URR recommend that forest stands are structurally more developed (Sohrabi *et al*., 2016) compared to CRR, potentially explaining higher carbon stock values observed in URR forests. Species such as *Combretum glutinosum* and *Combretum micranthum* are present in both regions, showing consistency in mid-level woody species across ecological zones. In grassland areas, woody spp. encroachment is evident, especially with species like *Combretum micranthum, Combretum glutinosum,* and *Lannea acida* appearing with substantial DBH and height. For example, *Lannea acida* shows a DBH of 49.67 cm in CRR grasslands and 50.8 cm in URR croplands, suggesting shrub-tree transition zones, potentially due to anthropogenic pressure or passive regrowth. Similar findings have been reported by Sohrabi *et al*., (2016). However, an alternative explanation, and probably a more plausible one, is that these large trees are remnants of forest stands that have been degraded into grassland.

Combretum micranthum is common in both CRR and URR grasslands, with taller specimens in URR (5 m average height) indicating a more robust vegetative structure. The presence of species with considerable DBH in grasslands (e.g., *Combretum nigerican* and *Strychnos spinosa*) reflects semi-wooded savanna systems, which are ecologically significant for biodiversity and carbon storage.

Tree presence in croplands is relatively limited, yet a few species, such as *Combretum glutinosum* and *Combretum micranthum,* persist, especially in URR. These species, known for their resilience and multiple uses (e.g., fuelwood, medicine), may be intentionally retained during land clearing due to their utility as observed by Aabeyir *et al*. (2016). The DBH values (e.g., *Combretum glutinosum* at 44.5 cm in URR) suggest that agroforestry practices or tree-crop systems might be contributing to above-ground carbon in cultivated landscapes. Settlements in URR show the presence of *Mangifera indica* (mango) with an exceptionally high average DBH of 95.5 cm and height of 12.1 m. This indicates urban greening or home garden practices, which have been increasingly recognized for their role in urban ecosystem services and carbon storage Dampha (2021). The low presence of trees in CRR settlements implies that either there is low community appreciation of trees or there are challenges with tree protection such as browsing by goats (Mousa *et al*. 2020).

Several species appear exclusively in URR, e.g., *Adansonia digitata, Azadirachta indica* and *Guiera senegalensis,* suggesting a playout of either regional ecological differences or human-driven planting preferences. Species like *Pterocarpus erinaceus* and *Sclerocarya birrea* are valuable both ecologically and economically and may reflect conservation or sustainable use practices in URR.

Table 4.2: Mean tree size (diameter in cm and height in m) for species enumerated in the CRR and URR

Blank spaces in the table indicate species absence from plots for the respective region and LULC

	Forest				Grassland				Cropland				Settlement			
	CRR		URR		CRR		URR		CRR		URR		CRR		URR	
Species	DBH	Height	DBH	Height	DBH	Height	DBH	Height	DBH	Height	DBH	Height	DBH	Height	DBH	Height
Acacia macrotachys	25.75	3.37	20.45	3.93	27.00	3.17										
Acacia seyal	17	4														
Bombax costatum	74	5														
Combretum glutinosum	33.63	4.16	32.6	4.86	33.31	3.35	24.00	4.61	39.43	3.51	44.5	4.5				
Combretum micranthum	19.85	3.79	20	5	16.00	2.80			15.58	2.79	15.24	2.85	15.5	2.25	15.17	2.35
Combretum nigerican	50	5	33.5	5	45.00	4.00			44.50	4.00						
Cordyla africana	10	3	123.4	7.3	0.00											
Lannea acida	56	4.33	9	6.67	49.67	3.67			50.80	3.60	55.25	3.75				
Pistigama thonningii	23	3			20.00	2.00										
Prosopis africana	76	5			70.00	4.00										

Strychnus spinosa	13	4.5	16.80	3.70	0.00											
Terminalia macroptera	68.2	7.4			65.00	5.50										
Vitex simpilicitiforlia	15.33	3	16.5	3.75	15.00	2.00			12.50	2.50	10	3	11	3	10	3
Ziziphus mauritania	42.5	6														
Adansonia digitata			109.00	14.00												
Azadirachata indica			85.00	3.05											89	3
Cassia sieberiana			19.08	3.64												
Guiera senegalensis			18.00	3.75												
Heeria insignis			20.00	4.00												
Mangifera indica			101.00	13.00											95.50	12.08
Pterocarpus erinaceous			126.00	8.00												
Sclerocarya birrea			50.00	7.00												
Terminalia glaucescence			22.00	3.50												
Vitex trifolia			22.73	4.14	22.17	3.75	22.17	3.75			19.5	5.5				

Voacanga africana	30.6	4

4.4.2 Above Ground Biomass (AGB) Distributions in the various LULC classes

The data presented in Table 4.3 compares the above-ground biomass (AGB) across four major land use land cover (LULC) classes: cropland, forest, grassland, and settlement, in CRR and URR of the Gambia. The table provides the mean AGB, as well as the minimum, maximum, and standard deviation of AGB values (in megagram per hectare, Mg/ha), reflecting the variation in biomass across each LULC type and region.

In cropland areas, both CRR and URR have relatively low mean AGB values, indicating limited biomass accumulation in agricultural lands. CRR records a mean AGB of 0.12 Mg/ha, slightly lower than URR's 0.14 Mg/ha. The standard deviations are also low (0.11 Mg/ha in CRR and 0.14 Mg/ha in URR), suggesting modest variability in cropland biomass. The maximum AGB values are below 0.5 Mg/ha in both regions, reinforcing the relatively low biomass associated with cultivated lands. Similar findings have been reported by Kucuker *et al.* (2015). Forests display the highest mean AGB among the LULC types, with URR showing a higher mean (0.76 Mg/ha) compared to CRR (0.64 Mg/ha). A statistical t-test was performed for the above-ground biomass mean values of CRR: 0.13Mg/ha, URR: 0.34Mg/ha. The URR region shows higher average biomass, suggesting potentially more productive or less degraded land cover. However, this difference is not statistically significant ($p = 0.069$).

More importantly, the range of AGB is much broader in forests, with maximum values reaching 11.26 Mg/ha in URR and 9.87 Mg/ha in CRR. The high standard deviations, 2.01 Mg/ha in URR and 1.72 Mg/ha in CRR, make the difference marginally non-significant ($p \approx 0.07$). However, with a larger sample, this difference might be significant. Normally the variability within dry forested areas, which is typical, given differences in tree density and forest maturity, may require large sample sizes to detect significant differences between different forest locations. Grasslands exhibit moderate biomass values, with URR showing only slightly higher AGB (mean of 0.20 Mg/ha) than CRR (0.16 Mg/ha). The AGB variability is somewhat greater in URR, reflected in a higher maximum value (1.04 Mg/ha) and a larger standard deviation (0.25 Mg/ha) compared to CRR (0.96 Mg/ha maximum, 0.19 Mg/ha standard deviation). No significant difference in carbon stocks in grasslands between the two regions was found. The means are relatively close, and variability is high, with $p = 0.50$. These values indicate limited but slightly more heterogeneous biomass storage in URR grasslands. Similar findings have been reported by (Kucuker *et al.*, 2015).

Settlement areas, while not typically associated with high biomass, show unexpectedly moderate AGB levels, particularly in URR, where the mean reaches 0.74 Mg/ha, higher than CRR's 0.18 Mg/ha. The variation is considerable in both regions, with maximum values of 3.30 Mg/ha in URR and 2.89 Mg/ha in CRR, and standard deviations of 0.89 and 0.77 Mg/ha, respectively. This is a statistically significant difference ($p < 0.05$). Settlements in URR have much higher above-ground carbon than those in CRR, possibly due to greater vegetation retention, urban greening, or different settlement typologies ($p = 0.010$). These results show similar potential to develop and maintain carbon stocks in settlements in the sub-humid zone of West Africa, as observed by Moussa *et al.* (2020) for Sahelian cities in Niger. The data show that forests and, to a lesser extent, settlements contribute the most to above-ground biomass in both regions, with URR generally having higher biomass values and variability than CRR across all LULC classes. This suggests that URR may hold greater carbon sequestration potential, particularly in forested and semi-developed landscapes.

Table 4.3: Above-ground biomass for CRR and URR based on carbon stocks on 20 individual plots, each measuring 2124 m^2 for each LULC type

LULC	Region	Mean AGB (Mg/ha)	Min AGB (Mg/ha)	Max AGB(Mg/ha)	Std Dev (Mg/ha)
Cropland	CRR	0.12	0.01	0.43	0.11
	URR	0.14	0.01	0.48	0.14
Forest	CRR	0.64	0.04	9.87	1.72
	URR	0.76	0.06	11.26	2.01
Grassland	CRR	0.16	0.00	0.96	0.19
	URR	0.20	0.01	1.04	0.25
Settlement	CRR	0.18	0.01	2.89	0.77
	URR	0.74	0.02	3.30	0.89

Table 4.4 provides estimates of above-ground carbon stocks (C_above) across five LULC classes in the CRR and URR of The Gambia. The figures reveal marked spatial variations in carbon storage potential between the two regions, highlighting the importance of LULC

types in regional carbon dynamics. Water bodies are not associated with any above-ground biomass and thus do not contribute to the above-ground carbon pool in either region. This is consistent with methodologies adopted by models such as InVEST and IPCC guidelines, which exclude open water surfaces from above-ground carbon estimates due to the lack of biomass (Touré and Rasmussen 2002).

Grasslands show relatively low carbon stocks, with CRR storing 0.08 Mg/ha, notably less than URR at 0.1 Mg/ha. Statistical test showed that there are no significant differences between these two regions in terms of carbon stock in the grassland (p = 0.545). This difference may reflect denser vegetation or the presence of bigger trees in the grassland ecosystems in CRR. Grasslands generally contribute modestly to carbon storage but play a significant role in maintaining soil carbon and biodiversity (Beyer *et al.*, 2022).

Settlements present an interesting contrast, with URR recording a substantially higher above-ground carbon stock (0.37 Mg/ha) compared to CRR (0.09 Mg/ha) (p = 0.004). This reflects the higher density of “urban” trees in URR. Urban greenery has been shown to significantly influence carbon dynamics in built environments, depending on tree canopy coverage and vegetation type Sohrabi et al. (2016). Croplands exhibit the lowest above-ground carbon values of the vegetated LULC classes, with CRR at 0.06 Mg/ha and URR slightly higher at 0.07 Mg/ha. This is consistent with previous research indicating that croplands, particularly those dominated by annual crops, contribute minimally to above-ground biomass carbon due to frequent harvests and low plant biomass (Aabeyir *et al.*, 2020). In the Gambia, rice is the dominant crop and to avoid bird pests, rice farmers would not normally retain many trees on their farms. Forests unsurprisingly have the highest above-ground carbon estimates, with URR storing 0.37 Mg/ha, and 0.09 Mg/ha observed in CRR. The significant difference lies in URR having more trees in forests than CRR, though the disparity is moderate. (p = 0.035). This aligns with numerous studies highlighting the critical role of forests in carbon sequestration due to their dense and perennial biomass (Aabeyir *et al.*, 2020). The disparity may indicate more intact forest cover, better forest management, or higher biomass density in URR, consistent with regional forest assessments (Aabeyir *et al.*, 2017).

Table 4.4: Carbon stock estimates for CRR and URR. Carbon stock was estimated from AGB by multiplying AGB by a factor of 0.5

		CRR	URR
Code	LULC Class	C_above (Mg/ha)	C_above (Mg/ha)
1	Water bodies	-	-
2	Grassland	0.08	0.1
3	Settlements	0.09	0.37
4	Cropland	0.06	0.07
5	Forest	0.32	0.38

Table 4.5 presents the predicted carbon stock, in Mg, across various LULC classes in the CRR from 2002 to 2034, as modeled by the InVEST Carbon Storage and Sequestration tool. The table reveals a significant shift in carbon storage patterns over time, driven by land use change dynamics such as deforestation, urban expansion, and agricultural development. Grassland, which held the largest share of carbon stock in 2002 (29,684.39 Mg), shows a consistent and substantial decline over the decades, dropping to 14,443.51 Mg by 2034, a reduction of over 50%. This decline suggests widespread conversion of grasslands to other land uses, particularly cropland and settlements. Such a LULCC trend, according to Wade *et al*. (2019), reflects increasing pressure on natural ecosystems in CRR, likely due to population growth, agricultural expansion, and development. Carbon stock within settlements increased significantly from 23.44 Mg in 2002 to 4,210.41 Mg in 2034. This more than 179-fold increase is indicative of urbanization and infrastructural growth, possibly including the establishment of urban trees or home gardens, which would slightly contribute to carbon stock despite generally low values associated with built-up areas. The dramatic rise, however, more likely reflects the spatial expansion of settlements and the associated reclassification of LULC types, absorbing former vegetated areas. Similar results have been reported by Bessah *et al.* (2019).

Cropland’s carbon stock rises significantly from 1,763.55 Mg in 2002 to 10,605.80 Mg by 2034. This six-fold increase highlights the agricultural transformation of CRR, as former grassland and forest areas are converted into farmland. While cropland generally has lower per-hectare carbon density compared to forests, the large-scale conversion of land contributes to its rising total stock. The gradual adoption of agroforestry or tree-integrated farming systems might also help retain some biomass and soil carbon. Similar findings have been reported by Liu *et al.* (2021). Forest carbon stock plummets from 1,059.72 Mg in 2002 to just 23.49 Mg by 2034, reflecting near-total deforestation. This 97.8% decrease is highly concerning, given the role of forests in long-term carbon storage, biodiversity, and climate regulation. The degradation and clearing of forests likely feed the growth in cropland and settlement areas. Such a dramatic reduction underscores the need for urgent forest protection and reforestation policies in CRR, Villamor *et al.* (2017).

The total carbon stock in CRR falls from 32,531.10 Mg in 2002 to 29,283.22 Mg in 2034, a modest but steady 10% decline over the 32 years. Similar findings have been reported by Villamor *et al.* (2017). While the overall loss may seem moderate, it conceals more severe ecosystem shifts, particularly the loss of high-carbon ecosystems like forests and grasslands, which are replaced by lower-carbon systems such as croplands and settlements Dampha (2021).

Table 4.5: Carbon stocks dynamics for CRR from 2002 to 2024 with prediction for 2034

LULC Class	2002	2013	2024	2034
Water bodies	-	-	-	-
Grassland	29684.39	24216.74	18623.73	14443.51
Settlements	23.44	305.88	3267.38	4210.41
Cropland	1763.55	5747.24	8225.17	10605.80
Forest	1059.72	97.74	50.83	23.49
Total	32531.10	30367.60	30167.11	29283.22

Table 4.6 presents the estimated carbon stock, in Mg, across different LULC classes in the URR of The Gambia from 2002 to 2034, based on the InVEST Carbon Storage and Sequestration model. The figures reveal profound transformations in land use, resulting in significant changes in carbon dynamics over time.

In 2002, grasslands accounted for 14,162.60 Mg of carbon, making them the primary carbon reservoir in URR. However, this value steadily declines to 6,983.52 Mg by 2034, representing a 50.7% reduction over 32 years. The decline indicates a progressive conversion of grassland to other land uses, notably croplands and settlements, similar to patterns observed in CRR. This ongoing degradation of natural grasslands undermines long-term ecosystem carbon storage (Wade *et al.,* 2019). Carbon stored in settlements grows exponentially from 322.54 Mg in 2002 to 15,323.92 Mg by 2034, a more than 47-fold increase. This surge reflects rapid urbanization and expansion of built-up areas, absorbing formerly vegetated lands, particularly grasslands and forests. The increase in settlement-related carbon stock is likely due to the spatial spread of urban greenery or misclassified areas where some vegetation remains (Dampha 2021). This trend also signals intense anthropogenic pressure on rural landscapes in the URR

Cropland carbon stock rises sharply from 834.36 Mg in 2002 to 9,075.67 Mg in 2034, representing a nearly 11-fold increase. This aligns with land conversion patterns, where grasslands and forests are cleared to expand farmland, possibly in response to population growth and food security needs. Although croplands store less carbon per hectare compared to forests, widespread expansion results in increased total carbon. Similar results have been obtained by Bessah *et al*. (2019). This growth also hints at possible agroforestry practices contributing to carbon retention. Forests in URR show a dramatic decline in carbon stock, from 378.89 Mg in 2002 to a mere 12.32 Mg by 2034, marking a reduction of over 96%. This highlights an alarming rate of deforestation and forest degradation, with grave implications for carbon sequestration, biodiversity, and ecological stability. Forests are likely to be cleared for settlement expansion and agriculture, suggesting an urgent need for reforestation and conservation efforts, as suggested by Bessah *et al.* (2019).

Contrary to trends seen in CRR, the total carbon stock in URR increases significantly, from 15,698.39 Mg in 2002 to 31,395.42 Mg in 2034, almost doubling over three decades. This increase is largely driven by the massive expansion of settlements and cropland, both of which now dominate the region's carbon stock. While the overall increase may appear positive, it masks the loss of high-carbon ecosystems (grassland and forest) and their replacement with lower-density but more widespread land uses (Dampha, 2021).

Table 4.6: Carbon stocks dynamics for URR from 2002 to 2024 with prediction for 2034

LULC Class	2002	2013	2024	2034
Water bodies	-	-	-	-
Grassland	14162.60	12009.91	8418.672	6983.52
Settlements	322.54	1389.80	10715.71	15323.92
Croplands	834.36	3816.15	7683.43	9075.67
Forest	378.89	156.04	56.78	12.32
Total	15698.39	17371.89	26874.60	31395.42

The spatial analysis of carbon stock from 2002 to 2034 at CRR (Figure 4.1) shows a progressive decline in high-carbon stock areas due to deforestation, land-use changes, and urban expansion. The transition from red (high-carbon areas) to green (low-carbon areas) highlights the loss of vegetation cover and carbon sequestration capacity over time. Deforestation and land-use changes significantly reduce carbon storage in natural ecosystems. Grassland and forest areas are shrinking, while agricultural and settlement areas are expanding, increasing carbon emissions. Projected trends for 2034 indicate a further decrease in carbon stock, which may contribute to climate instability and biodiversity loss. Without reforestation and conservation efforts, the region will experience reduced carbon sequestration potential, worsening the impacts of climate change.

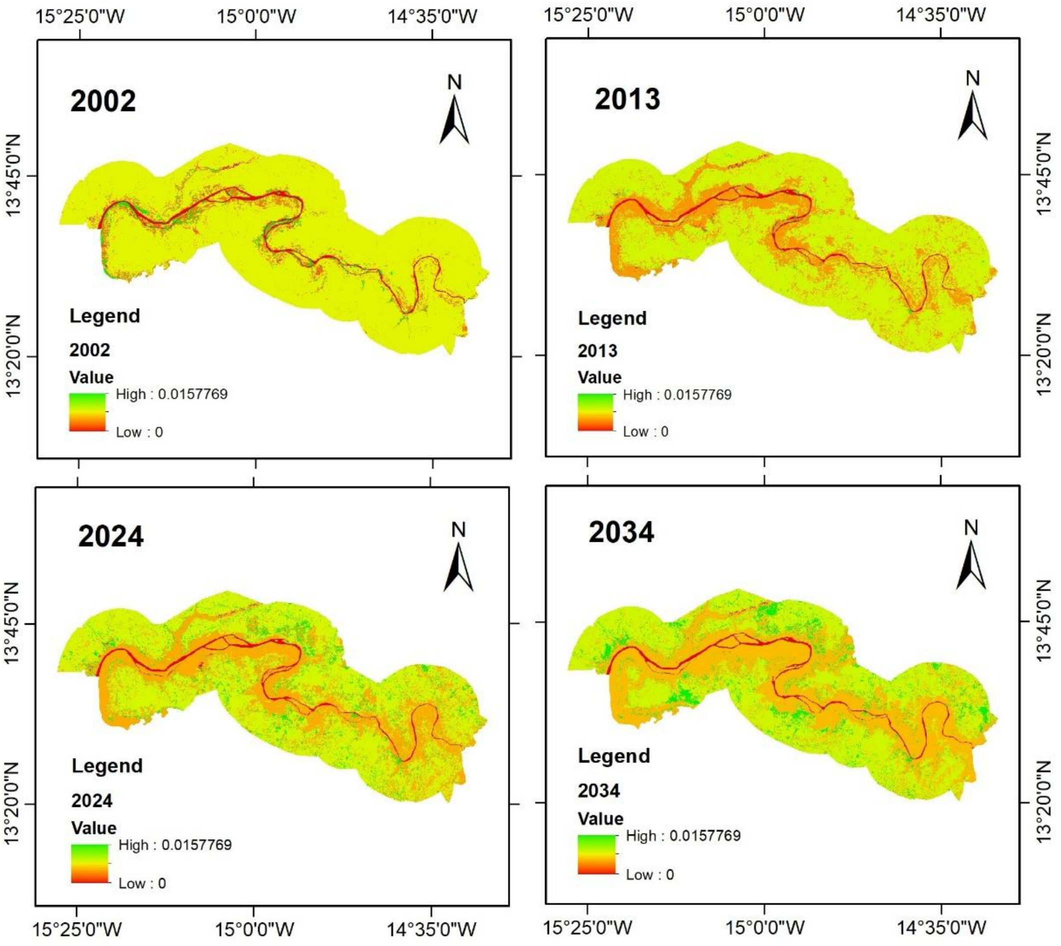

Figure 4.2: Carbon maps of the Central River Region (CRR)

The maps in Figure 4.2 illustrate carbon stock variations from 2002 to 2034 at URR, revealing a declining trend in high-carbon areas indicated by green and a growing dominance of low-carbon regions, indicated by orange-red. This pattern suggests land degradation, deforestation, and land-use changes, reducing carbon sequestration capacity. In 2002, most regions had moderate to high carbon stock, indicated by yellow-orange shades. By 2013, the carbon density had slightly decreased, showing early signs of deforestation and land-use transition.

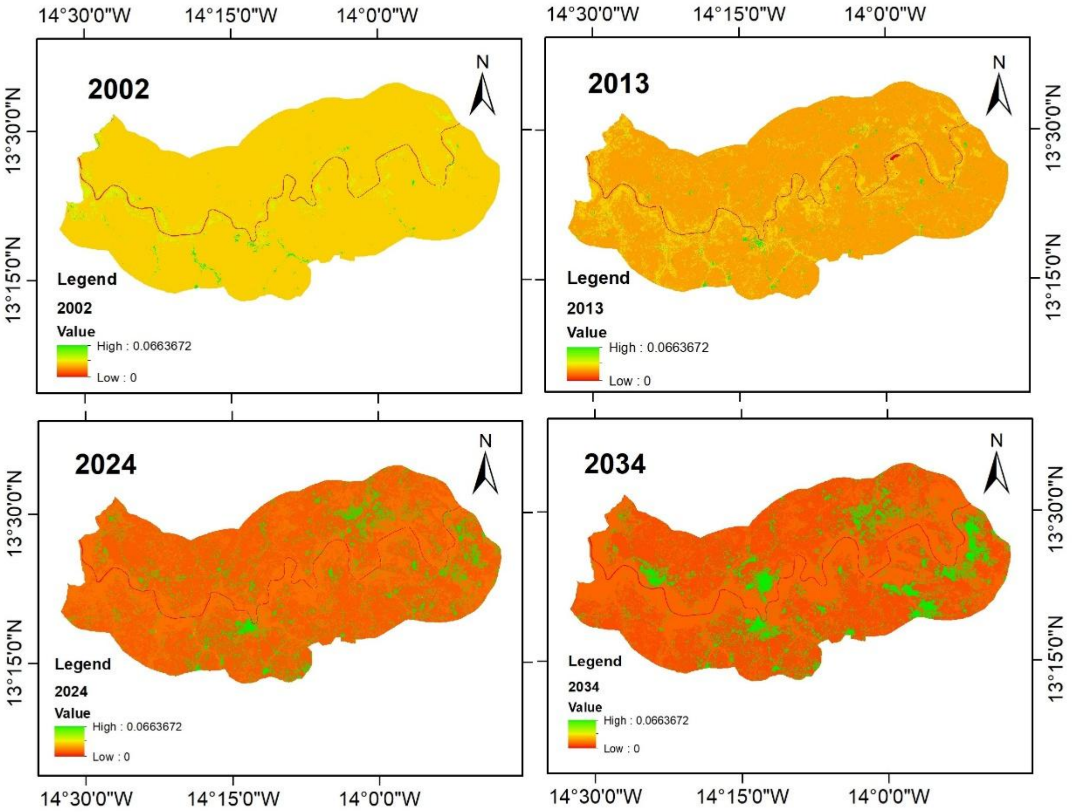

Figure 4.3: Carbon maps of the Upper River Region (URR)

4.5 Conclusions and Recommendations

4.5.1 Conclusions

The analysis of carbon stock dynamics showed in the CRR and URR of The Gambia from 2002 to 2034 reveals significant and divergent patterns in land use change and carbon storage. In CRR, total carbon stock declines steadily over the period, from 32,531.10 Mg in 2002 to 29,283.22 Mg in 2034. This reduction is primarily driven by the conversion of grasslands and forests to cropland and settlements. Notably, forest carbon drops drastically from 1,059.72 Mg in 2002 to just 23.49 Mg in 2034, reflecting widespread deforestation and forest degradation. This shift indicates a loss of high-density carbon ecosystems, with serious implications for ecological stability, biodiversity, and local climate regulation.

In contrast, URR exhibits an overall increase in carbon stock, rising from 15,698.39 Mg in 2002 to 31,395.42 Mg in 2034. However, this increase is deceptive; it stems from rapid urbanization and agricultural expansion, with settlement carbon growing by nearly 47 times, and cropland carbon rising more than tenfold. Meanwhile, natural ecosystems like forests and grasslands show sharp declines in carbon stock. Forest carbon falls from 378.89 Mg to 12.32 Mg, while grassland carbon drops by over 50%. These trends suggest that while total carbon increases, it is occurring at the cost of ecosystem integrity, shifting from stable, long-term carbon sinks to more vulnerable, human-modified landscapes.

4.5.2 Recommendations

Policy Recommendation

The Forestry Department of the Gambia should strengthen forest conservation, promote agroforestry, and urban greening to balance food production and settlement expansion with carbon sequestration goals.

Research Recommendation

Research institutions should develop climate-smart agricultural practices such as agroforestry to improve tree cover on croplands and also reduce forest and grassland conversion into croplands.

CHAPTER 5 USE OF FOREST PRODUCTS IN THE LIVELIHOODS OF RURAL COMMUNITIES OF THE CENTRAL RIVER AND UPPER RIVER REGIONS OF THE GAMBIA

5.1 Abstract

This study examines the demographic characteristics and their influence on the utilization of forest-related livelihoods in the Central River Region (CRR) and Upper River Region (URR) of The Gambia. A survey of 396 respondents revealed an average household size of 17.81 (SD = 16.66), with ages ranging from 27 to 65 years (M = 44.51, SD = 13.39). Gender distribution was nearly equal (M = 0.52, SD = 0.50), and educational attainment varied from primary to university level. Multivariate probit regression analysis indicated that gender significantly influenced the use of thatch ($\beta = 0.55$, $p < 0.001$) and timber ($\beta = 0.41$, $p = 0.008$), with males more likely to utilize these resources. A marginally significant negative association was observed between gender and bamboo use ($\beta = -0.33$, $p = 0.065$). Other factors, including household size, age, marital status, and education, did not show significant effects on resource utilization. Descriptive analyses showed that firewood and charcoal are the predominant forest-related livelihood activities in both regions, with CRR reporting 45.2% and 32.2%, respectively, and URR reporting 37.72% and 25.00%. Notably, timber production is more prominent in URR (18.10%) compared to CRR (4.3%), suggesting regional differences in resource dependence. These findings underscore the substantial reliance on forest resources for livelihoods in these regions and highlight the necessity for sustainable forest management practices to ensure the longevity and productivity of these essential resources. Land use and land cover change that reduces forest and tree cover in the rural landscapes of the CRR and URR would seriously undermine the populations' livelihoods.

5.2 Introduction

The Rice Value Chain Development Project (RVCDP), launched by the Gambia government, aims to enhance the rice production and processing capacities in the CRR and URR of The Gambia. This initiative is part of broader efforts to improve agricultural Production and productivity, ensure food security, and boost the economic livelihoods of rural communities. However, as agriculture expands, it is crucial to understand the potential environmental and socio-economic impacts, particularly on forest-related livelihoods vital for many communities in these regions. Several studies have highlighted the complex interplay between agricultural development and forest conservation. For instance, a study by Anderson and Eddelbuettel (2017) emphasized the importance of integrating sustainable agricultural practices to prevent deforestation and ensure the preservation of forest resources. Similarly, Brown (2014) discussed how agricultural projects, while beneficial for food security, can sometimes lead to unintended consequences such as forest degradation and biodiversity loss.

In the Gambia context, the forests in the CRR and URR provide essential ecosystem services, including the provision of non-timber forest products (NTFPs), which are crucial for the livelihoods of local communities. The reliance on these forests for fuelwood, medicinal plants, and other resources is well-documented in studies such as Sahoo *et al.* (2020), which explored the socio-economic benefits of forest resources in rural Gambian communities. Msofe *et al*. (2019) also underscored the significant role of forests in supporting the livelihoods of women and marginalized groups through the collection and sale of NTFPs. The RVCDP's implementation involves the transformation of rice farming practices, which includes the introduction of new technologies and the expansion of rice cultivation areas. Guzy *et al.* (2008) noted that such agricultural transformations can lead to increased land use pressure, potentially threatening forest areas. This aligns with findings of Perez-Garcia *et al.* (2002), who pointed out that agricultural intensification often comes at the expense of forest lands, leading to a loss of biodiversity and ecosystem services. Moreover, the economic upliftment from agricultural projects like the RVCDP can result in both positive and negative impacts on forest-related livelihoods. Chernozhukov *et al.* (2016), discussed how increased agricultural income can reduce dependence on forests for subsistence, thereby promoting conservation. Conversely, Villamor *et al.* (2017) highlighted cases where improved agricultural income led to more investments in agricultural expansion, further encroaching on forest lands Ziadat *et al.* (2021).

In assessing the potential effects of the RVCDP on forest-related livelihoods, it is essential to consider the multifaceted impacts on both the environment and the socio-economic fabric of local communities. As Sharma *et al.* (2017) pointed out, sustainable development requires a balance between agricultural advancement and environmental conservation. This balance is particularly critical in regions like CRR and URR, where forests play a central role in the livelihoods and cultural heritage of the people. Therefore, this study aims to determine the potential effects of the LULCC on forest-related livelihoods in the CRR and URR of The Gambia by examining the dependence of local communities on timber and non-timber forest products. The insights from this study could inform policy decisions and help design integrated approaches that support both agricultural development and forest sustainability.

5.3 Materials and Methods

5.3.1 Description of the study area

The study was conducted along the extensive floodplains of the River Gambia, located within the Central River Region (CRR) and Upper River Region (URR). Geographically, the area spans from longitude 15°27'43.905" W to 13°47'34.031"W and latitude 13°26'52.939"N to 13°38'19.187"N (Figure 1.1). It encompasses two of the country’s primary agroecological zones: the Sahel-Savannah Zone, also known as the Semi-Arid Zone, and the Sudano-Sahelian or Riverine Zone. The Sahel-Savannah Zone, spanning approximately 147,684 hectares in the extreme northern part of CRR, is characterized by its semi-arid climate, with limited surface water availability and erratic rainfall patterns averaging below 900 mm per year. These climatic conditions render rainfed crop production particularly challenging and unreliable. According to soil suitability assessments, only 28% of the land is classified as suitable for cultivation, whereas 21% is marginal and 36% is deemed unsuitable for agricultural activities (Von Luepke and Schoene, 2006). The combination of low and inconsistent precipitation, high evapotranspiration, and minimal water retention capacity of the soils further limits the region's agricultural potential. The Sudano-Sahelian or Riverine Zone, on the other hand, benefits from relatively better water availability due to its proximity to the River Gambia, yet still experiences similar climatic challenges. These environmental constraints significantly influence land use practices and necessitate innovative agricultural strategies to improve food security and livelihoods in the region (Brown, 1997).

5.3.2 Climate of the Area

The Gambia experiences a Sahelian climate, characterized by a long, dry season (November to May) and a short, wet season (June to October). Average temperatures in the Gambia range from 18°C to 30°C during the dry season and 23°C to 33°C during the wet season. Linear trends indicate that wet season (July, August, and September) rainfall in The Gambia has decreased significantly between 1960 and 2006, at an average rate of 8.8 mm per month per decade (Sanneh *et al*., 2022).

5.3.3 Socioeconomic activities of the area

CRR is notable for its extensive freshwater floodplains, making it ideal for rice cultivation and livestock rearing. The region has been central to agricultural development initiatives, such as the Jahally-Pacharr irrigation project and the Lowland Agriculture Development Program (LADEP), aimed at achieving food self-sufficiency. With a significant Fulani population traditionally known for cattle rearing, CRR is estimated to house over 50% of the country's cattle.

Despite its agricultural potential, CRR has the highest incidence of poverty in The Gambia, with levels around 60%. This is partly due to inadequate infrastructure, such as feeder roads, which hampers economic development and access to markets.

URR's economy is predominantly based on agriculture, with significant rice and groundnut production. Basse, the largest town, serves as a commercial hub, facilitating trade with neighboring countries like Senegal, Guinea, and Mali.

The inauguration of the URR Roads and Bridges Project in October 2021 enhanced connectivity, promoting the free movement of people, goods, and services, and is expected to boost economic activities in the region. In October 2024, the Trade

Facilitation West Africa (TFWA) Program was launched in Basse to support small-scale cross-border traders, particularly women, by providing training and raising awareness about trade rules and procedures.

Both regions are beneficiaries of the Regional Rice Value Chain Development Project (RRVCDP), a five-year initiative (2020-2025) aimed at increasing rice production and reducing reliance on imports. The project focuses on developing irrigation schemes, providing machinery, and constructing post-harvest infrastructure to support 80,000 beneficiaries across CRR and URR.

While both CRR and URR have significant agricultural potential, challenges such as poverty and infrastructural deficits persist. Ongoing initiatives aim to address these issues by enhancing agricultural productivity, improving infrastructure, and facilitating trade to foster economic growth in these regions.

5.3.4 Survey design

A household questionnaire was designed and administered in nine communities in each region. (Figure 5.1) Stratified random sampling was used to select 22 respondents from each community. Respondents were either farmers from the Rice Value Chain Project or not.

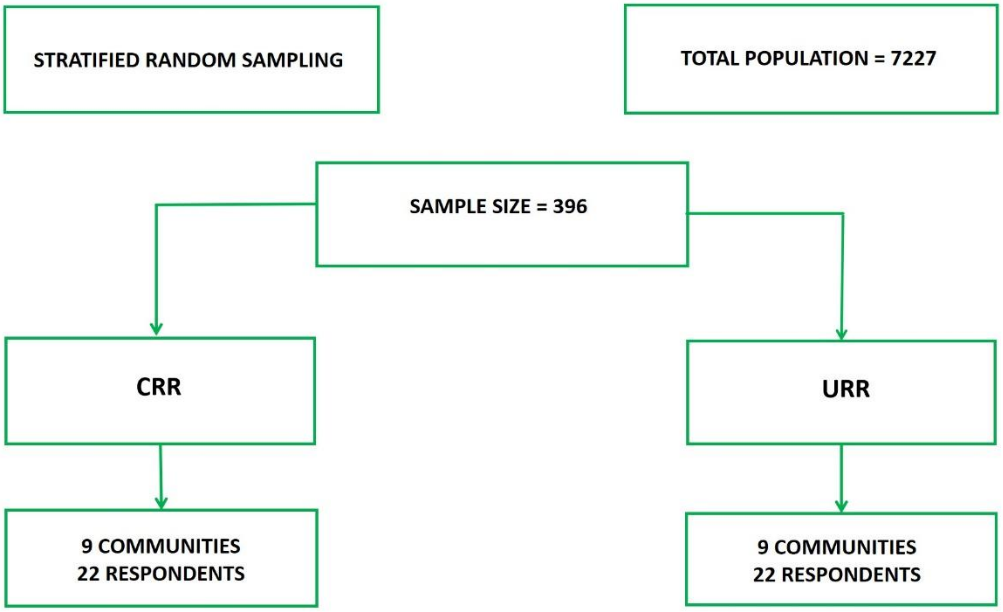

Figure 5.1: Sampling procedure and sampling techniques

The formula for known population (source: Adapted from Yamane, 1967)

$$n = \frac{N}{1 + N(e)^2}$$

Where:

N=Population Size

e= Confidence interval

n= Sample size

N= 7227, e = 0.05, n = 396

5.3.5 Data Collection

Tools questionnaire with A4 size Microsoft Office Word Forms was used to interview a total of 396 respondents, drawn from 22 households per community in each region.

5.3.6 Data analyses

The data was analysed using Stata 15.0 Descriptive statistical analysis and Multivariate probit were also done through regression analysis. Table 5.1 presents a detailed description of the variables used in the study, categorising them into dependent and independent variables. The dependent variable represents the sources of livelihood, specifically focusing on the type of forest product a household uses. These include firewood, charcoal, timber, and bamboo. Each forest product is recorded as a binary variable, where a value of 1 indicates that the household uses the respective product, while a 0 indicates otherwise. This categorisation allows for an analysis of the factors influencing household product choices. The independent variables are key demographic and socio-economic factors that may influence a household's choice. These were age, sex, size of household, and education as described below:

Age: A continuous variable representing the respondent's age in years.

Sex: variable where 1 represents Male and 0 represents Female.

Marital Status: variable, where 1 represents married individuals and 0 represents those who are unmarried.

Size of Household: continuous variable indicating the total number of individuals in a household.

Education: continuous variable measuring the number of years the respondent has spent in formal education.

These independent variables help assess how demographic and social characteristics influence the choice of livelihood sources, particularly in terms of household fuel usage.

Table 5.1: Socio-economic and demographic variables and description

Variable	Description
Dependent Variable	
Sources of Livelihood	
Firewood	1 if a household is using firewood; 0 otherwise
Charcoal	1 if a household is using charcoal; 0 otherwise
Thatch	1 if a household is using thatch; 0 otherwise
Timber	1 if a household is using timber; 0 otherwise
Bamboo	1 if a household is using bamboo; 0 otherwise
Independent Variable	
Age	This is a continuous variable of respondents' age in years
Sex	The gender of the respondents: 1 if Male, 0 for Female
Marital Status	1 if married; 0 otherwise
Size of Household	A continuous variable showing the number of individuals in the household
Education	A continuous variable showing the number of years in each level of education

5.4 Results and Discussion

5.4.1 Demographics of respondents

The demographic analysis of the Central River Region (CRR) and Upper River Region (URR) shows both similarities and key differences. Household sizes are mainly in the 25–34 age group (150 in CRR; 140 in URR), reflecting the continued presence of extended family systems typical in rural agrarian communities across sub-Saharan Africa. These large household sizes often relate to labor pooling strategies that support subsistence farming and communal living (Bah *et al.*, 2019; Mortimore, 2010).

The gender distribution shows a higher percentage of male respondents in both CRR (139) and URR (123), reflecting patriarchal norms where men often represent households in surveys and community decision-making. This gender imbalance aligns with wider trends in West Africa, where men usually hold more authority in land ownership and resource management (Doss et al., 2018).The age structure is concentrated within the economically active population, with fairly balanced representation in the 18–30, 31–40, and 41–60 cohorts, suggesting a robust labor force capable of sustaining agricultural and socio-economic activities. Similar demographic trends have been observed in other rural

Gambian regions, where youthful populations dominate, providing opportunities for agricultural intensification but also posing challenges of employment and migration (Jallow and Touray, 2020). Regarding marital status, the dominance of marriage (185 in CRR; 173 in URR) underscores its centrality as a social institution, while the higher incidence of widowhood in CRR (5) and divorce in URR (8) may reflect regional variations in cultural practices, mortality rates, and household vulnerability (Cham, 2018).

Educational attainment highlights persistent challenges. A significant proportion of respondents reported no formal education in both CRR (160) and URR (166), which mirrors national statistics indicating low literacy rates in rural Gambia (GBoS, 2022). While CRR records relatively higher participation in secondary education (13) compared to URR (2), URR shows slightly greater access to tertiary education (2) relative to CRR (1). These disparities reflect uneven educational opportunities and infrastructural distribution, with implications for adaptive capacity, innovation uptake, and climate resilience (UNDP, 2021).

Table 5.2: Descriptive statistical analysis

Variables	Category	CRR	URR
Region	2	1	1
Districts	10	5	5
Village	18	9	9
Household size	25-34	150	140
	15-24	37	35
	0-14	18	16
Sex	Male	139	123
	Female	81	53
Age	18–30	67	65
	31–40	64	62
	41–60	70	68
Marital status	Married	185	173
	Single	10	12
	Widow	5	1

	Divorced	2	8
Education background	Primary education	28	24
	Secondary education	13	2
	Tertiary education	1	2
	No formal education	160	166

5.4.2 Forest-Products Related Livelihood Observations in CRR and URR

Based on respondents' usage of products in the CRR, as showed in figure 5 firewood (and charcoal are the primary forest products used in livelihood activities, underscoring a significant reliance on traditional biomass for energy and income. Thatch serves as a moderate source of livelihood, while timber and bamboo are the least commonly utilized forest products. These findings align with previous studies, including those by Gioda *et al.* (2022).

In the URR, respondents also rely primarily on firewood although to a lesser extent than CRR. Similarly, charcoal production is lower in URR. However, thatch and timber have greater prominence in URR compared to CRR, suggesting a shift toward more diverse and possibly commercial forest utilization. Bamboo has the lowest representation in URR, even less than in CRR. Similar findings have been reported in Ghana by Amoah *et al.* (2015).

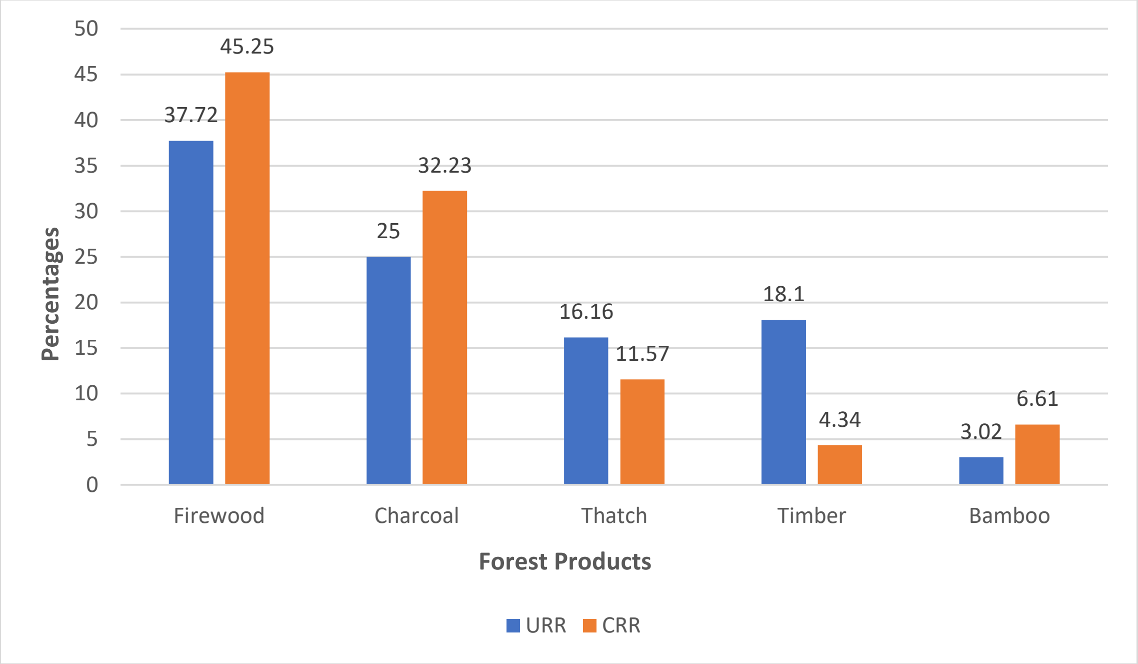

Figure 5.2: Percentage of respondents using various forest products for livelihood in the Central River Region (CRR) and Upper River Region (URR) of the Gambia.

5.4.3 Impact of household demographics on the likelihood of using different forest products

Regression analysis was used to examine the impact of household demographics on the likelihood of using different forest products, including firewood, charcoal, thatch material, timber and bamboo (Table 5.3). Statistically significant results ($p < 0.05$) indicate that the constant term negatively associates with using timber (-1.31, $p = 0.000$) and bamboo (-0.83, $p = 0.031$). Gender significantly influences the use of thatch (0.55, $p = 0.000$) and timber (0.41, $p = 0.008$), with males more likely to use these resources. Similar results have been obtained by Sahoo *et al.* (2020). A marginally significant negative association exists between gender and bamboo use (-0.33, $p = 0.065$). Similar results have been obtained by Ford *et al*. (2016).

Other variables, including household size, age, marital status, and education, showed no significant influence on resource use. However, education demonstrates a near-significant negative effect on thatch use (-0.03, $p = 0.054$), suggesting higher education may reduce reliance on thatch for roofing. Overall, the analysis highlights gender and baseline factors as key determinants of livelihood resource choices, particularly for timber and thatch, while suggesting that additional factors may influence resource use decisions. Similar findings have been reported by Nadarajah and Bakar (2013).

Table 5.3: Multivariate probit analysis results of the Impact of household demographics on the likelihood of using different forest products

Variable	**Firewood** **Coefficient (P>|z|)**	**Charcoal** **Coefficient (P>|z|)**	**Tach** **Coefficient (P>|z|)**	**Timber** **Coefficient (P>|z|)**	**Bamboo** **Coefficient (P>|z|)**
Constant	4.268	0.431	-0.3798	-1.311	-0.8340
	(0.322)	(0.170)	(0.236)	(0.000)**	(0.031)**
Household Size	0.018	-0.0004	0.0028	0.006	-0.00120
	(0.554)	(0.919)	(0.480)	(0.133)	(0.824)
Age	-0.0123	-0.005	-0.0058	-0.0028	0.0035
	(0.563)	(0.409)	(0.310)	(0.643)	(0.616)
Sex	0.169	0.0646	0.5499	0.4067	-0.3278
	(0.774)	(0.656)	(0.000)**	(0.008)**	(0.065)
Marital Status	-1.241	0.2863	-0.0477	0.4545	-0.287
	(0.770)	(0.199)	(0.838)	(0.086)	(0.252)
Education	-0.073	-0.0053	-0.0325	0.020	-0.0217
	(0.185)	(0.747)	(0.054)	(0.232)	(0.299)

Notes: p-values are in parentheses, ** means P-value is significant at 0.05

5.4.4 Income categories for all forest-dependent livelihoods in CRR and URR

Table 5.4 illustrates the distribution of forest-dependent livelihoods by income category in the CRR and URR of The Gambia. It reveals a stark disparity in forest product use across economic groups, showing that the poorest households dominate the use of firewood, charcoal, thatch, timber, and bamboo, with usage rates above average for all products. This pattern reflects a strong dependence on forest resources among the lowest income groups, consistent with broader trends observed in many rural parts of West Africa and other developing regions. Similar findings have been reported by Shackleton *et al.* (2021) and Gioda *et al.* (2022).

The "poorest" category makes up of firewood users of charcoal users of thatch users of timber users, and of bamboo users. These high percentages indicate that forest products play a vital role as safety nets for basic needs, especially energy, housing, and income support, among economically vulnerable households. In contrast, the "poor" and "moderately poor" categories account for a combined of usage across most products, while the "better-off" and "slightly better-off" households make up less than 1%, with several zero values, particularly in bamboo and thatch use. This downward gradient in forest product reliance from the poorest to the better-off is indicative of a poverty-driven dependence on forest ecosystems, where improved income allows households to shift toward alternative energy sources or more durable building materials. Similar results have been obtained by Reed *et al.*,(2021) Njana and Sangeda, (2022).

The overreliance of the poorest on forest resources such as charcoal and firewood, especially in CRR and URR, also raises sustainability concerns. High extraction pressure from this group could worsen forest degradation if not accompanied by sustainable harvesting practices or access regulations. Similar concerns are expressed by Adepoju and Oyewole (2023). Furthermore, without alternative income sources or energy options, attempts to restrict forest access may disproportionately impact the most economically marginalized groups, as noted by Kissinger *et al.* (2023). This data underscores the importance of integrating pro-poor forest governance frameworks, which not only protect forest ecosystems but also prioritize the livelihood security of the rural poor. Policy interventions should focus on livelihood diversification, improved forest management, and energy access programs targeted at low-income households to reduce forest products overreliance and vulnerability (FAO, 2021).

Table 5.4: Income categories for all forest-dependent livelihoods in CRR and URR

Income categories	Firewood %	Charcoal %	Thatch%	Timber %	Bamboo%
Poorest	97.47	98.74	98.23	97.98	99.49
Poor	1.26	0.51	1.01	1.01	0.25
Moderately poor	0.75	0.25	0.51	0.51	0.25
Better	0.25	0.25	0.25	0.25	0.00
Slightly Better	0.25	0.00	0.00	0.00	0.00

5.4.5 Forest Products Income for Households

Table 5.5 presents the average monthly income per household derived from key forest products: charcoal, firewood, thatch, timber, and bamboo, in the Central River Region (CRR) and Upper River Region (URR) of The Gambia. In CRR, charcoal generates an average household income of making it a significant source of revenue. Firewood yields a much lower income suggesting it is either sold in smaller quantities or primarily used for subsistence rather than for income. Similar findings have been obtained by Aabeyir *et al.* (2017). Interestingly, thatch income is absent the CRR record, indicating that households either do not sell thatch, use it exclusively for domestic purposes, or it is underreported. Timber shows the highest income in CRR highlighting it as the most commercially valuable forest product in this region. Bamboo, although not as widespread, contributes a considerable reflecting its smaller niche yet valuable market role.

In contrast, URR households show a higher income from charcoal and firewood, both surpassing CRR figures ($X^2 = 6901.38$, p-value< .05). This suggests either more efficient market access or higher market prices. Thatch, which was unrecorded in CRR, contributes ($130) per household in URR, reflecting its greater commercial relevance in this region. Timber income in URR is slightly lower than CRR's, but still substantial, pointing to its role as a consistent income generator. Notably, bamboo generates the highest income in URR making it the region's most lucrative forest product per household. This contrasts with CRR, where timber leads instead. Similar findings have been obtained by Gioda *et al.* (2022). In the present study, the average firewood consumption was 1,297± 952kg person^{-1}year$^{-1,}$ which is substantially higher than the national estimated average of 560 kg person^{-1}year^{-1} (FAO, 2021)$^{.}$ These results show that on-site measurements differ from those estimated by official agencies, and studies such as this are essential for assessing local firewood use accurately.

Table 5.5: Average Income generated per Household per month per region (USD) exchange rate 1 USD =60 GMD (Gambian Dalasi)

Region	Mean Income Charcoal	Mean Income firewood	Mean Income Thatch	Mean Income Timber	Mean Income Bamboo
CRR	$375	$41.67	$0	$438	$550
URR	$450	$58.33	$ 130	$450	$500

The data indicate that households in the Central River Region (CRR) exhibit a significantly higher reliance on biomass fuels compared to those in the Upper River Region (URR). On average, the test yielded a Chi-Square value of ($\chi^2 = 0.27$ with a p-value of 0.60), indicating no statistically significant difference in charcoal use between the two regions. Furthermore, all respondents in both regions reported using firewood, households in CRR collect of firewood per month (approximately 157.5 kg), while URR households collect only (112.5 kg). Similarly, charcoal consumption is markedly higher in CRR, where households use an average of 752.5 kg, compared to 322.5 kg in URR. This suggests that CRR households are more dependent on biomass for their energy needs, possibly due to limited access to alternative energy sources such as liquefied petroleum gas (LPG) or electricity, or due to economic factors that favor continued reliance on traditional fuels (Matocha *et al.*, 2020; IEA, 2021). The greater intensity of biomass usage in CRR may also reflect variations in household size, cooking practices, or forest availability. These patterns are consistent with findings from rural Sub-Saharan Africa, where firewood and charcoal remain dominant energy sources despite efforts to promote cleaner alternatives (van der Kroon *et al.*, 2013). Excessive reliance on biomass fuels has significant environmental and health implications, including deforestation, land degradation, and exposure to harmful indoor air pollutants (World Bank, 2020). Understanding regional differences in consumption patterns is therefore essential for informing sustainable energy and forest management strategies in The Gambia.

Table 5.6: Quantity of firewood and charcoal consumed calculated in kg/month per household.

Region	**Firewood (kilograms)**	**Charcoal (kilogram)**
CRR	157.5	752.5
URR	112.5	322. 5

5.5 Conclusions and Recommendations

5.5.1 Conclusions

The results of this study, which examined the dependence of rural communities of the CRR and URR of the Gambia on forest products for livelihoods, highlight the critical role forest resources play in rural livelihoods, particularly in energy and income generation. In CRR, 45.2% of households rely on firewood and 32.2% on charcoal as primary sources of livelihood, whereas in URR, the figures are 37.72% and 25.00% respectively. Timber (18.10%) and thatch (16.16%) usage in URR suggests a trend toward more diverse and possibly commercial forest utilization, compared to CRR (timber 4.3%, thatch 11.6%). Gender significantly influences forest product utilization: males are more likely to use thatch ($\beta = 0.55$, $p < 0.001$) and timber ($\beta = 0.41$, $p = 0.008$). Education negatively correlates with thatch usage ($\beta = -0.0325$, $p = 0.054$), implying that higher educational attainment may lead to the use of manufactured roofing materials.

5.5.2 Recommendations

Policy Recommendation

Tailor tree- management interventions to regional and gender contexts, recognizing the differences in resource availability and extraction, particularly the higher timber extraction in URR, to ensure more effective and targeted resource management strategies.

Research Recommendation

Promote the expansion of agroforestry and reforestation initiatives, especially in regions experiencing significant forest loss. Encourage the use of native and multipurpose tree species to rehabilitate degraded lands while supporting local livelihoods.

CHAPTER 6 GENERAL DISCUSSION

This study revealed significant changes in land use and land cover (LULC) in the Central River Region (CRR) and Upper River Region (URR) of The Gambia between 2002 and 2024. The results show sharp declines in forest and grassland, alongside marked increases in cropland and settlement. These patterns broadly align with global and regional research but also show notable local differences in trajectory and magnitude. In the CRR, forest cover declined dramatically by 95.2%, while the URR experienced an 85% decline. Similar large-scale forest losses due to agricultural expansion were documented by Rimal *et al.* (2019) in Nepal and Dampha (2021) in The Gambia. However, the slightly lower decline in URR may reflect localized interventions, such as tree planting initiatives, which echo results by Mbow *et al.* (2015) in Senegal, where afforestation programs buffered forest loss. Grassland reductions were also significant (37.3% in CRR and 40.6% in URR), consistent with Esch *et al.* (2017) and Faye *et al.* (2020), who reported that land clearing for agriculture is widespread in the Sahel. Methodologically, these studies, like ours, relied on satellite imagery, but they differed in classification algorithms, which may partly explain variations in estimated rates of loss. The expansion of cropland and settlements (82–100%) mirrors global findings on urban growth and agricultural expansion (Seto *et al.*, 2012; FAO, 2016). In the URR, settlement growth more than doubled by 2024 (14,526.36 ha), a trend also noted by Forkuor *et al.* (2013) in West African towns. Water bodies exhibited moderate to substantial reductions (12.3% in CRR; 19.4% in URR), comparable to those reported by Degu *et al.* (2019) in East Africa, where irrigation demands and damming were identified as contributing factors to water losses. Such consistency across different regions suggests common drivers, particularly population pressure and agricultural intensification. The implications for carbon dynamics were striking. In CRR, total carbon stock decreased from 32,531.10 Mg in 2002 to 30,167.11 Mg in 2024, driven by the near-complete loss of forest carbon. These results are comparable to Duku et al. (2015) in Ghana, who found steady declines in carbon stocks due to cropland expansion. In contrast, URR’s carbon stock rose from 15,698.39 Mg to 26,874.60 Mg over the same period. This increase is misleading, however, as it reflects carbon accumulation in cropland and settlement trees, not in natural ecosystems. This supports Houghton and Nassikas (2017), who argued that human-modified landscapes accumulate carbon at the expense of ecological integrity. The divergent trends between CRR and URR demonstrate how regional differences in land management (e.g., settlement greening in URR) can shape carbon outcomes even under broadly similar pressures. The livelihood dimension reinforces the ecological findings. In CRR, households rely heavily on firewood (45.2%) and charcoal (32.2%), while URR shows more diversified forest product use, with timber (18.1%) and thatch (16.16%) playing a greater role. These results are consistent with Shoo *et al.* (2020), who found gender significantly influenced timber and thatch use in Tanzania. The strong poverty-forest link observed here, where 97% of users fall into the poorest income group, supports global findings by Wunder et al. (2020) and Shackleton *et al.* (2021). Importantly, bamboo's contribution to household income in URR (USD 500/month) parallels results by Gioda *et al.* (2022) in Asia, underscoring bamboo's growing role in rural livelihoods. The comparative perspective suggests that while the magnitude of LULC change in The Gambia mirrors trends observed across Africa and beyond, the dynamics of carbon and livelihoods diverge between CRR and URR. This divergence highlights the influence of localized interventions, ecological context, and livelihood patterns on shaping outcomes. Similar findings have been reported by Reed *et al.* (2021) and Njana *et al.* (2022), who emphasized that the poorest communities bear the heaviest costs of environmental degradation. The study confirms that rapid LULC change poses severe risks to ecosystems and livelihoods, consistent with regional and global research. However, the contrasting results between CRR and URR highlight opportunities for adaptive management. Programs such as agroforestry and settlement greening, if scaled, could mitigate forest loss and maintain carbon stocks, as also advocated by Mbow *et al.* (2015).

CHAPTER 7 GENERAL CONCLUSIONS

The analysis of land use land cover (LULC) change from 2002 to 2024 in the Central River Region (CRR) and Upper River Region (URR) of The Gambia shows marked shifts driven by agricultural expansion and urban development. Forest cover declined dramatically, with CRR declining approximately 95.2% and URR losing 85% of their forest area by 2024. Grasslands also experienced substantial reductions of 37.3% in CRR and 40.6% in URR, largely due to conversion to cropland. In contrast, cropland areas increased sharply, by 100% in CRR and 82% in URR, while settlement areas expanded by more than 100% in both regions, reflecting rapid population growth and infrastructure development. Water bodies also shrank moderately, with CRR experiencing a 12.3% loss and URR a 19.4% reduction, likely due to seasonal variability, damming, and increased irrigation demands. Between 2024 and 2034, croplands are projected to make the highest net gains (28.9% in CRR and 18.1% in URR), mainly through conversions from grassland. Settlements will also expand significantly, especially in URR (42.9%). Grasslands are projected to decrease by 22.5% in CRR and 17.0% in URR. Forests and water bodies will also decline, with forest area dropping by -78.31% in CRR and 16.28% in URR. These changes highlight the increasing intensity of human land use and the replacement of natural ecosystems with cropland and settlement.

In terms of carbon dynamics, CRR exhibited a steady decline in total carbon stock, falling from 32,531 Mg in 2002 to 29,283 Mg in 2034, largely due to forest and grassland degradation. Forest carbon dropped dramatically from 1,059 Mg to 23 Mg. Conversely, URR showed an apparent increase in total carbon stock from 15,698 Mg to 31,395 Mg. However, this increase reflects the expansion of croplands and settlements, carbon sources that are less stable than forests and grasslands. Forest carbon in URR declined sharply from 379 Mg to 12 Mg, and grassland carbon dropped by over 50%, signaling significant ecological degradation despite higher carbon totals.

The greater intensity of biomass usage in CRR may also reflect variations in household size, cooking practices, or forest availability. These patterns are consistent with findings from rural Sub-Saharan Africa, where firewood and charcoal remain dominant energy sources despite efforts to promote cleaner alternatives (van der Kroon *et al.*, 2013). Excessive reliance on biomass fuels has significant environmental and health implications, including deforestation, land degradation, and exposure to harmful indoor air pollutants (World Bank, 2020). Understanding regional differences in consumption patterns is therefore essential for informing sustainable energy and forest management strategies in The Gambia. The study also highlights the socio-economic dependency of rural households on forest products. In CRR, 45.2% of households rely on firewood and 32.2% on charcoal; in URR, the respective figures are 37.7% and 25.0%. Timber and thatch use is more diverse in URR (18.1% and 16.2%) than in CRR (4.3% and 11.6%). Households in both regions depend on forest-based livelihoods. Gender and education influence resource use, with males more likely to exploit timber and thatch, while higher education levels are negatively associated with traditional thatch use, indicating a shift toward manufactured products in buildings.

REFERENCES

Aabeyir, R. et al. (2016) 'Empirical evidence of the impact of commercial charcoal production on Woodland in the Forest-Savannah transition zone, Ghana', Energy for Sustainable Development, 33, pp. 84–95. doi: 10.1016/j.esd.2016.03.005.

Aabeyir, R. et al. (2017) 'Multi-Level Land Cover Change Analysis in the Forest-Savannah Transition Zone of the Kintampo Municipality, Ghana', Journal of Natural Resources and Development, 7(1), pp. 1–11. doi: 10.5027/jnrd.v7i0.01.

Aabeyir, R. et al. (2020) 'Allometric models for estimating aboveground biomass in the tropical woodlands of Ghana, West Africa', Forest Ecosystems, 7(1). doi: 10.1186/s40663-020-00250-3.

Ahmadalipour, A. et al. (2019) 'Future drought risk in Africa: Integrating vulnerability, climate change, and population growth', Science of the Total Environment, 662, pp. 672–686. doi: 10.1016/j.scitotenv.2019.01.278.

Allaire, J., Eddelbuettel, D. and François, R. (2013) 'Rcpp Attributes', R package version 0.10, pp. 1–12. Available at: http://ftp.iitm.ac.in/cran/web/packages/Rcpp/vignettes/Rcpp-attributes.pdf.

Amoah, M., Marfo, O. and Ohene, M. (2015) 'Firewood consumption pattern, availability and coping strategies adopted to mitigate firewood scarcity: A case of rural households in Ghana', Forests Trees and Livelihoods, 24(3), pp. 202–218. doi: 10.1080/14728028.2015.1052854.

Ampim, P. A. Y. et al. (2021) 'Land cover changes in ghana over the past 24 years', Sustainability (Switzerland), 13(9). doi: 10.3390/su13094951.

Anderson, G. B. and Eddelbuettel, D. (2017) 'Hosting Data Packages via drat: A Case Study with Hurricane Exposure Data', The R Journal, 9(1), pp. 486–497. Available at: https://journal.r-project.org/archive/2017/RJ-2017-026/index.html.

Arfasa, G. F., Owusu-Sekyere, E. and Doke, D. A. (2023) 'Predictions of land use/land cover change, drivers, and their implications on water availability for irrigation in the Vea catchment, Ghana', Geocarto International, 38(1), p. doi: 10.1080/10106049.2023.2243093.

Aronson, J., & Alexander, S. (2013). Ecosystem restoration is now a global priority: Time to roll up our sleeves. *Restoration Ecology, 21*(3), 293–296. https://doi.org/10.1111/rec.12011

Baffoe-andrews, w. (2024) 'urban growth and livelihood transformation on the fringes of kumasi metropolis : a case of bosomtwe district in ghana'.

Bah, O. (2019) 'Land Use and Land Cover Dynamics in Central River Region of the Gambia, West Africa from 1984 to 2017’, American Journal of Modern Energy, 5, p. 5. doi: 10.11648/j.ajme.20190502.11.

Bah, A., et al. (2019). Agricultural transformations and rural livelihoods in West Africa. Journal of Rural Studies, 68, 11–21.

Banger, K., Tian, H. and Tao, B. (2015) ‘Contemporary land cover and land use patterns in India estimated by different regional and global data sets’, Journal of Land Use Science, 10(1), pp. 95–107. doi: 10.1080/1747423X.2013.858786.

Bessah, E. et al. (2019) ‘The impact of crop farmers’ decisions on future land use, land cover changes in Kintampo North Municipality of Ghana’, International Journal of Climate Change Strategies and Management, 11(1), pp. 72–87. doi: 10.1108/IJCCSM-05-2017-0114.

Beyer, R. M. et al. (2022) ‘Relocating croplands could drastically reduce the environmental impacts of global food production’, Communications Earth and Environment, 3(1), pp. 1–11. doi: 10.1038/s43247-022-00360-6.

Biro, K. et al. (2013) ‘Land Use/Land Cover Change Analysis And Its Impact On Soil Properties In The Northern Part Of Gadarif Region, Sudan’, Land Degradation and Development, 24(1), pp. 90–102. doi: 10.1002/ldr.1116.

Bivand, R. (2015) ‘OGR shapefile encoding’, CRAN Repository, pp. 1–6.

Brown, S. (1997) Estimating Biomass and Biomass Change of Tropical Forests: a Primer. (FAO Forestry Paper -134), A Forest Resources Assessment publication. Edited by F. A. O. F. paper. Roma: FAO - Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/W4095E/W4095E00.htm.

Brown, S. (2014) ‘Measuring and Monitoring Changes in Carbon Stocks’, pp. 1–13.

Buabeng, D. F., Yankson, E. and Mensah, P. (2025) ‘Role of Customary Land Governance in Sustainable Development in Africa : A Namibian Context’, © Springer Nature Switzerland AG 2025.

Cavus, M. and Yazıcı, B. (2021) ‘Testing the equality of normal distributed and independent groups’ means under unequal variances by doex package’, The R Journal, 12(2), pp. 134–154. Available at: https://journal.r-project.org/archive/2021/RJ-2021-008/index.html.

Ceesay, A. et al. (2017) ‘Mangrove Vegetation Dynamics of the Tanbi Wetland National Park in The Gambia’, Environment and Ecology Research, 5(2), pp. 145–160. doi: 10.13189/eer.2017.050209.

Chave, J. et al. (2005) ‘Tree allometry and improved estimation of carbon stocks and balance in tropical forests’, Oecologia, 145(1), pp. 87–99. doi: 10.1007/s00442-005-0100-x.

Chave, J. et al. (2014) ‘Improved allometric models to estimate the aboveground biomass of tropical trees’, Global Change Biology, 20(10), pp. 3177–3190. doi: 10.1111/gcb.12629.

Cham, M. (2018). Marriage, family, and kinship systems in The Gambia. African Sociological Review, 22(1), 45–62.

Chen, S. et al. (2022) ‘Trends in Research on Forest Ecosystem Services in the Most Recent 20 Years : A Bibliometric Analysis’, pp. 1–19.

Chernozhukov, V., Hansen, C. and Spindler, M. (2016) ‘hdm: High-Dimensional Metrics’, The R Journal, 8(2), pp. 185–199. Available at: https://journal.r-project.org/archive/2016/RJ-2016-040/index.html.

Chishugi, D. U. et al. (2021) ‘How climate change and land use/land cover change affect domestic water vulnerability in Yangambi Watersheds (D. R. Congo)’, Land, 10(2), pp. 1–21. doi: 10.3390/land10020165.

Coulibaly, O. N. (2021, January 19). Mali – Land, climate, energy, agriculture and development: A study in the Sudano-Sahel Initiative for Regional Development, Jobs, and Food Security (ZEF Working Paper No. 199). Center for Development Research (ZEF), University of Bonn. https://doi.org/10.22004/ag.econ.308805.

Crosson, P. et al. (2011) ‘A review of whole farm systems models of greenhouse gas emissions from beef and dairy cattle production systems’, Animal Feed Science and Technology, 166–167, pp. 29–45. doi: 10.1016/j.anifeedsci.2011.04.001.

Dahan, K. S. and Kasei, R. A. (2022) ‘Overview of Researches on Bush Fires for Natural Resources and Environmental Management in Ghana: A Review’, Environment and Natural Resources Research, 12(1), p. 48. doi: 10.5539/enrr.v12n1p48.

Dampha, N. (2020) ‘Ecosystem {Services} and {Coastal} {Adaptation} to {Climate} {Change}: {An} {Interdisciplinary} {Science}-{Based} {Application} in {The} {Gambia}’, (September). Available at: http://conservancy.umn.edu/handle/11299/217791.

Dampha, Nfamara K (2021) ‘Change detection (1985-2020): Projections on land-use land cover, carbon storage, sequestration, and valuation in Southwestern Gambia’, Sustainable Environment, 7(1). doi: 10.1080/23311843.2021.1875556.

Dayamba, S. D. et al. (2016) ‘Biodiversity and carbon stocks in different land use types in the Sudanian Zone of Burkina Faso, West Africa’, Agriculture, Ecosystems and Environment, 216(January), pp. 61–72. doi: 10.1016/j.agee.2015.09.023.

Degu, A. M., Hossain, F., Niyogi, D., Burian, S., Shepherd, J. M., & Pielke, R. A. (2019). The influence of large dams on surrounding climate and precipitation patterns. Environmental Research Letters, 6(3), 034006.

Dibba, B. et al. (2025) ‘Land Cover Transformation and Population Growth: Impacts on

Coastal Environment of The Gambia (1990–2020)’, Sustainability (Switzerland), 17(5), pp. 1–15. doi: 10.3390/su17051853.

Doss, C., Meinzen-Dick, R., Quisumbing, A., & Theis, S. (2018). Women in agriculture: Four myths. Global Food Security, 16, 69–74.

Duku, C., Hein, L., & Vlek, P. L. G. (2015). Land use dynamics and carbon stocks in Ghana. Environmental Management, 55(2), 396–410.

Emiru, T., Naqvi, H. R. and Athick, M. A. (2018) ‘Anthropogenic impact on land use land cover: influence on weather and vegetation in Bambasi Wereda, Ethiopia’, Spatial Information Research, 26(4), pp. 427–436. doi: 10.1007/s41324-018-0186-y.

Esch, T. van, Krueger, A., Bachofer, F., Heldens, W., Hirner, A., & Roth, A. (2017). Scenarios for the UNCCD Global Land Outlook. In: UNCCD Technical Report (p. 115). Bonn: UNCCD.

FAO (2016) Forests and agriculture: land-use challenges and opportunities, State of the World’s Forests. Available at: http://ccafs.cgiar.org/news/press-releases/agriculture-and-food-production-contribute-29-percent-global-greenhouse-gas.

Food and Agriculture Organization of the United Nations (FAO). (2021).The state of the world’s forests 2020: Forests, biodiversity and people. Rome: FAO. https://doi.org/10.4060/ca8642.

FAO. (2020). The State of the World’s Forests 2020: Forests, biodiversity and people. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/ca8642en

Flade, L., Hopkinson, C. and Chasmer, L. (2020) ‘Allometric equations for shrub and short-stature tree aboveground biomass within boreal ecosystems of Northwestern Canada’, Forests, 11(11), pp. 1–16. doi: 10.3390/f11111207.

Fonji, S. F. and Taff, G. N. (2014) ‘Using satellite data to monitor land-use land-cover change in North-eastern Latvia’, SpringerPlus, 3(1), pp. 1–15. doi: 10.1186/2193-1801-3-61.

Ford, A. T., Fryxell, J. M. and Sinclair, A. R. E. (2016) ‘Conservation Challenges Facing African Savanna Ecosystems’, Antelope Conservation: From Diagnosis to Action, (June), pp. 11–31. doi: 10.1002/9781118409572.ch2.

Faye, C., Tappan, G. G., & Sall, M. (2020). Land cover change and its impact on ecosystem services in the Ferlo region of Senegal. Journal of Land Use Science, 15(3), 341–358.

Forkuor, G., Conrad, C., Thiel, M., & Ullmann, T. (2013). Evaluation of Landsat and RapidEye data for land use and land cover mapping in northern Ghana. GIS science & Remote Sensing, 50(4), 437–457.

Francis, G. and Sena, A. A. (2022) ‘Climate Change and Rainfall Variability in West Africa :

Food Climate Change and Rainfall Variability in West Africa : Food Security and Farmer Coping Strate- Gies : a Review', 10(August), pp. 261–266.

Fuchs, R., Prestele, R. and Verburg, P. H. (2018) 'A global assessment of gross and net land change dynamics for current conditions and future scenarios', pp. 441–458.

GBoS (Gambia Bureau of Statistics). (2022). Population and Housing Census Report. Banjul, The Gambia.

Gebeyehu, G. et al. (2020) 'Allometric equations for aboveground biomass estimations of four dry Afromontane tree species', 4, pp. 1–24.

Gibbs, H. K. et al. (2007) 'Monitoring and estimating tropical forest carbon stocks: Making REDD a reality', Environmental Research Letters, 2(4). doi: 10.1088/1748-9326/2/4/045023.

Gioda, A. et al. (2022) 'Evaluation of baseline firewood consumption for domestic cooking ilow-income rural households in Bahia, Brazil', Acta Botanica Brasilica, 36, pp. 1–8. doi: 10.1590/0102-33062021abb0275.

Goldewijk, K. K. and Ramankutty, N. (2004) 'Land cover change over the last three centuries due to human activities : The availability of new global data sets Author (s): Kees Klein Goldewijk and Navin Ramankutty Source : GeoJournal , Vol . 61, No .4, Understanding Land-Use Change to Reconstru', GeoJournal, 61(4), pp. 335–344.

Guzy, M. R. et al. (2008) 'Policy research using agent-based modeling to assess future impacts of urban expansion into farmlands and forests', Ecology and Society, 13(1).doi: 10.5751/ES-02388-130137.

Haynes, P. and Yongfu, H. (2014). Policies and measures for mitigating climate change, Decarbonising the World's Economy: Assessing the Feasibility of Policies to Reduce Greenhouse Gas Emissions. doi: 10.1142/9781783265121_0003.

Heng, L. (2021) Measuring Emission of Agricultural Greenhouse Gases and Developing Mitigation Options using Nuclear and Related Techniques, Measuring Emission of Agricultural Greenhouse Gases and Developing Mitigation Options using Nuclear and Related Techniques. doi: 10.1007/978-3-030-55396-8.

Hoffmann, J. (2021). Demographic Change and Land Use. doi: 10.1007/978-3-030-50841-8_4.

Hu, X., Yang, S. and Cai, M. (2016) 'Contrasting the eastern Pacific El Niño and the central Pacific El Niño: process-based feedback attribution', Climate Dynamics, 47(7–8), pp. 2413–2424. doi: 10.1007/s00382-015-2971-9.

IPCC. (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of

Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009325844.

Jallow, M., & Touray, L. (2020). Youth employment and migration trends in rural Gambia. African Development Review, 32(4), 512–525.

Jose, S. (2012). Agroforestry for conserving and enhancing biodiversity. *Agroforestry Systems, 85*(1), 1–8. https://doi.org/10.1007/s10457-012-9517-5

Kissinger, G., Herold, M., & De Sy, V. (2023). Drivers of deforestation and forest degradation: A synthesis report for REDD+ policymakers. CIFOR. https://doi.org/10.17528/cifor/003657.

Kola-Mustapha, A. T. et al. (2023) ‘Evaluation of Terminalia macroptera (Combretaceae) Guill. & Perr stem bark extract incorporated into an emulgel for the potential management of rheumatoid arthritis’, Scientific African, 19, p. e01557. doi: 10.1016/j.sciaf.2023.e01557.

Kucuker, M. A. et al. (2015) ‘Impact of deforestation on soil carbon stock and its spatial distribution in the western black sea region of Turkey’, Journal of Environmental Management, 147(September), pp. 227–235. doi: 10.1016/j.jenvman.2014.08.017.

Kumi-Boateng, B., Mireku-Gyimah, D. and Duker Kumi-Boateng, A. A. (2015) ‘A Spatio-Temporal Based Estimation of Carbon in the Tarkwa Mining Area of Ghana’, Ghana Mining Journal, 15(1), pp. 10–21.

Kuyah, S. et al. (2020). Potential of Agroforestry to Enhance Livelihood Security in Africa, Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges-Vol.1. doi: 10.1007/978-981-15-4136-0_4.

Lee, H. et al. (2022) IPCC Sixth Assessment Report - Synthesis Report, Intergovernmental Panel on Climate Change, 2023.

Liu, Y. et al. (2021) ‘Rice paddy soils are a quantitatively important carbon store according to a global synthesis’, Communications Earth and Environment, 2(1). doi: 10.1038/s43247-021-00229-0.

Liyew, M., Tsunekawa, A. and Haregeweyn, N. (2019) ‘Land Use Policy Exploring land use / land cover changes , drivers and their implications in contrasting agro-ecological environments of Ethiopia’, Land Use Policy, 87(March), p. 104052. doi: 10.1016/j.landusepol.2019.104052.

Mekonnen, Z. et al. (2018) ‘Remote Sensing Applications : Society and Environment Land use and land cover changes and the link to land degradation in Arsi Negele district , Central Rift Valley , Ethiopia’, Remote Sensing Applications: Society and Environment, 12(July), pp. 1–9. doi: 10.1016/j.rsase.2018.07.012.

Moussa, S. et al. (2020) ‘Diversity and structure of urban forests of Sahel cities in Niger’, Urban Ecosystems, 23(4), pp. 851–864. doi: 10.1007/s11252-020-00984-6.

Mortimore, M. (2010). Adapting to drought in the Sahel: Lessons for climate change adaptation in West Africa. Environmental Science & Policy, 13(8), 116–124.

Msofe, N. K., Sheng, L. and Lyimo, J. (2019) ‘Land Use Change Trends and Their Driving Forces in the Kilombero Valley Floodplain, Southeastern’. doi: 10.3390/su11020505.

Muñoz-Rojas, M. et al. (2015) ‘Impact of Land Use and Land Cover Changes on Organic Carbon Stocks in Mediterranean Soils (1956-2007)’, Land Degradation and Development, 26(2), pp. 168–179. doi: 10.1002/ldr.2194.

Murtishaw, S., Sathaye, J. and LeFranc, M. (2006) ‘Spatial boundaries and temporal periods for setting greenhouse gas performance standards’, Energy Policy, 34(12), pp. 1378–1388. doi: 10.1016/j.enpol.2004.10.020.

Nadarajah, S. and Bakar, S. A. A. (2013) ‘CompLognormal: An R Package for Composite Lognormal Distributions’ The R Journal, 5(2), pp. 97–103. Available at: https://journal.r-project.org/archive/2013/RJ-2013-030/index.html.

Nel, L. et al. (2022) ‘InVEST Soil Carbon Stock Modelling of Agricultural Landscapes as an Ecosystem Service Indicator’, Sustainability (Switzerland), 14(16), pp. 1–19. doi: 10.3390/su14169808.

Nget, S. et al. (2011) ‘The Gambia – National Forest Assessment 2008-2010’, p. 131. Available at: http://www.fao.org/forestry/28636-042de4909ac624064c9c42f1fae43c57a.pdf.

Ochuka, M. et al. (2019) ‘Land Use/Land Cover Dynamics and Anthropogenic Driving Factors in Lake Baringo Catchment, Rift Valley, Kenya’, Natural Resources, 10(10), pp. 367–389. doi: 10.4236/nr.2019.1010025.

Perez-Garcia Joyce, L.A., McGuire, D., Xiao, X., J. (2002) ‘Impacts of climate change on the global forest sector’, Climate Change, (54), pp. 439–461.

Prestele, R. et al. (2017) ‘Current challenges of implementing anthropogenic land-use and land-cover change in models contributing to climate change assessments’, Earth System Dynamics, 8(2), pp. 369–386. doi: 10.5194/esd-8-369-2017.

Ramankutty, N. et al. (2008) ‘Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000’, Global Biogeochemical Cycles, 22(1), pp. 1–19. doi: 10.1029/2007GB002952.

Rimal, B. et al. (2018) ‘Land use/land cover dynamics and modeling of urban land expansion by the integration of cellular automata and markov chain’, ISPRS International Journal of Geo-Information, 7(4). doi: 10.3390/ijgi7040154.

Rimal, B., Sharma, R., Kunwar, R., & Stork, N. E. (2019). Forest cover change and ecosystem service valuation in the Himalayas. Sustainability, 11(2), 504.

Rookmaaker, L. C. (2020) Culture in Africa, Bibliography of the Rhinoceros. doi: 10.1201/9781003079057-13.

Sahoo, M., Nayak, H. and Mohanty, T. L. (2020) 'Role of socio-economic variables and non-timber forest products on the livelihood dependency of forest fringe communities in Khordha forest division, Odisha', Researchgate.Net, (December 2019). doi: 10.13140/RG.2.2.16140.95361.

Sanneh, L., Babana, A. H. and Yaffa, S. (2022) 'Assessment of Farmers Perception about Climate Change Impact and Adaptation Strategies Use for Tomato Production inThe Gambia', Journal of Agricultural Studies, 10(4), p. 27. doi: 10.5296/jas.v10i4.20278.

Seddon, N. et al. (2020) 'Understanding the value and limits of nature-based solutions to climate change and other global challenges', Philosophical Transactions of the Royal Society B: Biological Sciences, 375(1794). doi: 10.1098/rstb.2019.0120.

Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences, 109(40), 16083–16088.

Seyam, M. M. H., Haque, M. R. and Rahman, M. M. (2023) 'Identifying the land use land cover (LULC) changes using remote sensing and GIS approach: A case study at Bhaluka in Mymensingh, Bangladesh', Case Studies in Chemical and Environmental Engineering, 7(November 2022), p. 100293. doi: 10.1016/j.cscee.2022.100293.

Sharma, R. et al. (2017) 'Simulating Noisy, Nonparametric, and Multivariate Discrete Patterns', The R Journal, 9(2), pp. 366–377. Available at: https://journal.r-project.org/archive/2017/RJ-2017-053/index.html.

Sohrabi, H., Bakhtiarvand-Bakhtiari, S. and Ahmadi, K. (2016) 'Above- and below-ground biomass and carbon stocks of different tree plantations in central Iran', Journal of Arid Land, 8(1), pp. 138–145. doi: 10.1007/s40333-015-0087-z.

Solly, B. et al. (2021) 'Detection of recent changes in Gambia vegetation cover using time series MODIS NDVI', Belgeo, (1), pp. 0–14. doi: 10.4000/BELGEO.47995.

Song, W. and Deng, X. (2017) 'Land-use/land-cover change and ecosystem service provision in China', Science of the Total Environment, 576, pp. 705–719. doi: 10.1016/j.scitotenv.2016.07.078.

Steffens, C. et al. (2022) 'Tree species affect the vertical distribution of soil organic carbon and total nitrogen', Journal of Plant Nutrition and Soil Science, 185(6), pp. 864–875. doi: 10.1002/jpln.202200165.

Sutton, P. C. et al. (2016). The ecological economics of land degradation: Impacts on ecosystem service values', Ecological Economics, 129, pp. 182–192. doi: 10.1016/j.ecolecon.2016.06.016.

Swamy, S. L. et al. (2023) 'Carbon stock dynamics in a disturbed tropical forest ecosystem of Central India: Strategies for achieving carbon neutrality', Ecological Indicators, 154(August), p. 110775. doi: 10.1016/j.ecolind.2023.110775.

Tahmasebi, T., Karami, E. and Keshavarz, M. (2020) 'Agricultural land use change under climate variability and change: Drivers and impacts', Journal of Arid Environments, 180(February), p. 104202. doi: 10.1016/j.jaridenv.2020.104202.

Tarawally, M. et al. (2019) 'Land use/land cover change evaluation using land change modeller: A comparative analysis between two main cities in Sierra Leone', Remote Sensing Applications: Society and Environment, 16(September), p. 100262. doi: 10.1016/j.rsase.2019.100262.

Tarawally, M. et al. (2019) 'Land use/land cover change evaluation using land change modeller: A comparative analysis between two main cities in Sierra Leone', Remote Sensing Applications: Society and Environment, 16(September), p. 100262. doi: 10.1016/j.rsase.2019.100262.

Tappan, G., Sall, M., Wood, E., & Cushing, M. (2004). Ecoregions and land cover trends in Senegal. Journal of Arid Environments, 59(3), 427–462.

Temesgen, H. et al. (2021) 'Remote Sensing Applications : Society and Environment Modeling and prediction of effects of land use change in an agroforestry dominated southeastern Rift-Valley escarpment of Ethiopia', Remote Sensing Applications: Society and Environment, 21(December 2020), p. 100469. doi: 10.1016/j.rsase.2021.100469.

Thenkabail, P. S. (2015). Remotely sensed data characterization, classification, and accuracies, Remotely Sensed Data Characterization, Classification, and Accuracies. doi: 10.1201/b19294.

Thiam, S. et al. (2022) 'Modelling Land Use and Land Cover in the Transboundary Mono River Catchment of Togo and Benin Using Markov Chain and Stakeholder's Perspectives', Sustainability (Switzerland), 14(7). doi: 10.3390/su14074160.

UNDP (2021). Human Development Report: The Gambia. United Nations Development Programme.

Vågen, T. G., Lal, R. and Singh, B. R. (2005) 'Soil carbon sequestration in sub-Saharan Africa: A review', Land Degradation and Development, 16(1), pp. 53–71. doi:

10.1002/ldr.644.

Van Esch, S., Prado, A., & Pacheco, P. (2017). *Scenarios for the UNCCD Global Land Outlook* (p. 115). United Nations Convention to Combat Desertification (UNCCD).

Villamor, G. B. et al. (2017) 'Tree-cover transition in Northern Vietnam from a gender-specific land-use preferences perspective', Land Use Policy, 61, pp. 53–62. doi: 10.1016/j.landusepol.2016.11.002.

Villamor, G. B. et al. (2019) 'Contrasting stakeholder and scientist conceptual models of food-energy-water systems: a case study in Magic Valley, Southern Idaho', Socio-Environmental Systems Modelling, 2, p. 16312. doi: 10.18174/sesmo.2020a16312.

Wade, A. M. et al. (2019) 'Estimates and determinants of stocks of deep soil carbon in Gabon, Central Africa', Geoderma, 341(January), pp. 236–248. doi: 10.1016/j.geoderma.2019.01.004.

Walker, S. M. et al. (2012) 'Module C-CS: Calculations for estimating carbon stocks', Leaf technical guidance series for the development of a forest carbon monitoring system for REDD+, pp. 1–44.

Watson, J. E. M., Dudley, N., Segan, D. B., & Hockings, M. (2014). The performance and potential of protected areas. *Nature, 515*(7525), 67–73. https://doi.org/10.1038/nature13947

Wmo (2005) Climate and Land Degradation Climate and Land Degradation. Available at: http://www.wmo.int/pages/themes/wmoprod/documents/WMO989E.pdf.

Wolde, S. G., D'Odorico, P. and Rulli, M. C. (2023) 'Environmental drivers of human migration in Sub-Saharan Africa', Global Sustainability, 6. doi: 10.1017/sus.2023.5.

Yamane, T. (1967). Statistics: An introductory analysis (2nd ed.). Harper & Row. https://doi.org/10.2307/2282703

Yigini, Y. and Panagos, P. (2016) 'Assessment of soil organic carbon stocks under future climate and land cover changes in Europe', Science of the Total Environment, 557–558(April 2016), pp. 838–850. doi: 10.1016/j.scitotenv.2016.03.085.

Zanne, A. E. et al. (2009) 'Global wood density database', Dryad. Identifier: http://hdl.handle.net/10255/dryad.

Ziadat, F. M. et al. (2021) 'An Overview of Land Degradation and Sustainable Land Management in the Near East and North Africa', Sustainable Agriculture Research, 11(1), p. 11. doi: 10.5539/sar.v11n1p11.

APPENDICES

Appendix 1A

Variable	Description
Dependent Variable Sources of Livelihood	
Firewood	1 if a household is using Firewood; 0 otherwise
Charcoal	1 if a household is using Charcoal; 0 otherwise
Tach	1 if a household is using Kerosene; 0 otherwise
Timber	1 if a household is using Agro-residue; 0 otherwise
Bamboo	1 if a household is using Bamboo; 0 otherwise
Independent Variable	
Age	This is a continuous variable of respondents' age in years
Sex	The gender of the respondents: 1 if Male, 0 for Female
Marital Status	1 if married; 0 otherwise
Size of Household	A continuous variable showing the number of individuals in the household
Education	A continuous variable showing the number of years in each level of education

Appendix 1B

Determine the potential effect of LULC Change on forest-related livelihoods in the CRR and URR of the Gambia.

Purpose: The purpose of this survey is to gather information on the impact of land use land cover change on forest-related livelihoods in the central and upper river regions in the Gambia.

Confidentiality Notice: Your responses are voluntary, and the information you provide will be handled with the utmost confidentiality. WASCAL and KNUST are the only organizations/institutes that reserve the right to use and disseminate the information provided in this survey.

Household survey Questionnaire No

Village Identification ……………………………………………..

General Information………………………………………..

Village ID……………………………………………………

Name of District……………………………………………….

Region Name: ………………………………………………….

GPS coordinates………….Latitude……….Longitude………………….

Name of Interviewer: …………………………………………………..

Date of Interview: ……………………………………………………...

Part I: Household detail of respondents/Interviewer

1. Name of Respondent…………………………………
2. Household size (number of individuals in the household) [ ]
3. Is the respondent the head of the household? 1= yes, 2= No
4. Sex of respondent 1= male ( ) 2 = Female ( )
5. Age of respondent 1=18—30 2= 31-40 3= 41—60 4= above 60
6. Marital status of respondent 1. Single 2. Married 3. Divorced 4. Widowed 5. separated
7. Religion 1. Christian 2. Muslim 3. others
8. Educational Background 1=Non-literate 2= **Read and write 3= Primary school 1-4 4=Junior secondary school 5-8 5=Secondary school 9-12 6=Tertiary college and university____________

Part II: Key Questions to be answered from the questionnaire (Respondent)

1. **Firewood:**

Are you depending on firewood for subsistence (domestic use) only? (a) [yes] [No]

ii. Are you using firewood for commercial purposes?

(b) [yes] [No]

iii. How much firewood (headloads) do you harvest from the (i) Forest, (ii) grassland, (iii) Cropland per week for domestic use?

(c) ( ) ( ) ( )

1. How much firewood (headloads) do you harvest from the Forest per week for domestic use?
2. How much firewood (headloads) do you harvest from the grassland per week for domestic use?
3. How much firewood (headloads) do you harvest from the Cropland per week for domestic use?

iv. How much firewood do you harvest per week for commercial purposes (i) Forest (ii) grassland (iii) Cropland?

( ) ( ) ( )

1. How much firewood do you harvest from the forest per week for commercial purposes?
2. How much firewood do you harvest from grassland per week for commercial purposes?
3. How much firewood do you harvest from cropland per week for commercial purposes?

How much money do you get from selling firewood/month?

What are your other sources of income?

1. Do you get a source of income from farming? (a) yes (b) no
2. Do you get a source of income from sand mining? (a) yes (b) no

(i)………………………(ii) ………………………(iii)…………….(iv)

3. How much money do you get from other sources of income?

(f)…………………………………………………………………….

vii. At what time of the year do you get more income from the forest?

Farming season or Off-farming season

That income constitutes what percentage of total firewood income?

(g)……………………………………………………..

viii. What is the income from firewood used for?

(h)……………………………………………………….

ix. What would you do without firewood income?

(i)……………………………………………………………..

2. Charcoal.

i. Are you dependent on charcoal as a subsistence only?

(a) [yes] (b) [No]

ii. Are you using charcoal for commercial purposes?

(a) [yes], (b) [No]

iii. How much charcoal do you produce for domestic use from the options below?

(i) Forest (ii) grassland(iii) Cropland?

(c) ( ) ( ) ( )

iv. How much charcoal do you produce for commercial use from the options below?

(i) forest (ii) grassland (iii)cropland?

(d) ( ) ( ) ( )

1. How much charcoal do you produce for domestic use from the forest?
2. How much charcoal do you produce for domestic use from grassland?

3. How much charcoal do you produce for domestic use from cropland?

vi. How much charcoal do you produce for commercial use from the underlisted options?

(i) forest (ii) grassland (iii)cropland? (d)

( ) ( ) ( )

1. How much charcoal do you produce for commercial use from the forest?
2. How much charcoal do you produce for commercial use from the grassland?
3. How much charcoal do you produce for commercial use from the cropland?

How much money did you get from selling charcoal/month?

What are your other sources of income?

1. Do you get a source of income from farming? (a) yes (b) no
2. Do you get a source of income from sand mining? (a) yes (b) no

(e) (i)………………………(ii) ………………………(iii)…………….(iv)

vi. How much money do you get from other sources of income?

(f)……………………………………………………………………….

vii. At what time of the year do you get more income from charcoal production?

Farming season or Off-farming season

That income constitutes what percentage of total charcoal income?

(g)…………………………………………………………….

viii. What is the income from charcoal used for?

(h)…………………………………………….

ix. What would you do without a charcoal income?

(i)………………………………………………………….

3. Food from forest/savanna (fruit, honey, spices, tubers, vegetables, etc) from the forest?

I. Mention the types of food your household obtains from the forest/savanna. Example fruits, honey, spices, tubers, vegetables, etc?

(a)

iii. Which of the food types do you harvest for domestic purposes?

(i)………………………(ii) ………………………(iii)…………….(iv)

Where do you harvest these food types from (i) Forest
……………………………….. (ii) Savanna……………………………. (iii)
Cropland?...

For each food type, what quantities are harvested per month/season for domestic use?

(c) ( ) ( ) ( )

iv. For each food type what quantities are harvested per month/season for commercial use?

Food type	Forest	Grassland	Cropland

(d) Forest ( ) and savanna ( )

v. How much money do you get from selling these fruits/month?

What are your other sources of income?

1. Do you get a source of income from farming? (a) yes (b) no
2. Do you get a source of income from sand mining? (a) yes (b) no

(e) (i)………………………(ii) ………………………(iii)…………….(iv)

vi. How much money do you get from other sources of income?

(f) ……………………………………………………………….

vii. At what time of the year do you get more income from wild foods from the forest/ grassland and cropland?

(i) Farming season (ii) off-farm season

(g) That income constitutes what percentage of total wild food income?

viii. What is the income from wild foods used for?

(h)……………………………………………………..

ix. What would you do without wild food income?

(i)………………………………………

4. **Thatch Users:**

i. Are you depending on thatch as subsistence (domestic) only?

(a) [yes] [No]

ii. Are you depending on thatch as a commercial activity?

(b) [yes] [No]

iii. How much thatch (headload) do you harvest for subsistence use from (i) Forest, (ii) grassland, (iii) Cropland?

(c) ( ) ( ) ( )

iv. How much thatch do you harvest (commercial users) from the

(i) Forest (ii) grassland (iii) Cropland?

(d) ( ) ( ) ( )

1. How much thatch (headloads) do you harvest for subsistence (domestic) use from the forest?
2. How much thatch (headloads) do you harvest for subsistence (domestic) use from grassland?
3. How much thatch (headloads) do you harvest for subsistence (domestic) use from cropland?

How much thatch do you harvest (commercial users) from the Forest?

How much thatch do you harvest (commercial users) from the grassland?

How much thatch do you harvest (commercial users) from the cropland?

How much money do you get from selling the thatch/month?

What are your other sources of income?

(e) (i)………………………(ii) ………………………(iii)…………….(iv)

1. Do you get a source of income from farming? (a) yes (b) no
3. Do you get a source of income from sand mining? (a) yes (b) no

How much money do you get from other sources of income?

(f)………………………………………………………………………………

vii. At what time of the year do you get more income from thatch materials?

(i) Farming season (ii) Off-farming season

That income constitutes what percentage of total income from thatch?

viii. What is the income from thatch used for?

(h)……………………………………………….

ix. What would you do without thatch income?

(i)………………………………………………..

5. **Timber and poles:**

i. Are you dependent on timber and poles for subsistence only? (a) (Domestic) [yes] [No]

ii. Are you dependent on timber and poles as a commercial activity?

(b) (Domestic) [yes] [No]

iii. How much timber do you harvest for subsistence use (domestic use only)?

(i) Forest (ii) Savanna (iii) Cropland?

(c) ( ) ( ) ( )

vi. How much timber and poles do you harvest for commercial purposes from the Forest?

How much timber and poles do you harvest for subsistence from the Forest?
How much timber and poles do you harvest for subsistence from the grassland?
How much timber and poles do you harvest for subsistence from the Cropland?

iv. How much timber do you harvest (commercial users) from the forest?

(d)………………………………………………………………………..

1. How much timber and poles do you harvest (commercial users) from the forest?

2. How much timber do you harvest (commercial users) from the grassland?

3. How much timber and poles do you harvest (commercial users) from the cropland?

How much money did you get from selling timber/month? What are your other sources of income?

(e)…………………………………………………………………………

How much money do you get from other sources of income?

(f)………………………………………………………………………

vii. At what time of the year do you get more income from the forest (What percentage of total timber income?

(g) time……………. Percentage.........................

viii. What is the income from timber used for?

(h)……………………………………………………………

ix. What would you do without timber income?

(i)…………………………………………………..

6. Value chain

I. How many people trade in each of the above commodities?

(a)

Item	No. of traders	Trade destination	How often do traders visit the community	Estimated quantity of goods bought/trip
Firewood				
Charcoal				
Wild food				
Poles/timber				
Thatch materials				

ii. How much income do you make?

(b) ( )

iii. What are your other sources of income?

(c) ……………………………………………………………..

iv. What percentage of your income is derived from trading in the commodity?

(d)……………………………………………………………

v. What would you do in the absence of the commodity?

(e)………………………………………………………………

6. Bamboo

i. Do you depend on bamboo for subsistence (domestic use) only?

Yes [ ] No [ ]

ii. Do you depend on bamboo for commercial purposes?

Yes [ ] No [ ]

ii. How much bamboo do you harvest for subsistence use from:

How much bamboo do you harvest for subsistence from the forest?
How much bamboo do you harvest for subsistence from the grassland?
How much bamboo do you harvest for subsistence from the cropland?

iii. Forest ( ); Grassland ( ); Cropland ( )

xiii. iv. How much bamboo do you harvest for commercial use from: Forest ( ); Grassland ( ), Cropland ( ) ?

1. How much bamboo do you harvest for commercial use from the forest?
2. How much bamboo do you harvest for commercial use from the grassland?
3. How much bamboo do you harvest for commercial use from the cropland?

1. How much money do you get from selling the bamboo?

xv. What are your other sources of income?

Do you get a source of income from farming? (a) yes (b) no
Do you get a source of income from sand mining? (a) yes (b) no

How much money do you get from other sources of income?

xvii. At what time of the year do you get more income from bamboo?

Farming season [ ] Off-farming season [ ]

xviii. That income constitutes what percentage of total income from timber/poles?

xix. What is the income from the bamboo used for? ……………………….

xx. What would you do without bamboo income?
………………………………………………..

xxi. Apart from the listed items, what other benefits (environmental resources do you derive from the forest, grassland or cropland?

Benefit Forest Grassland

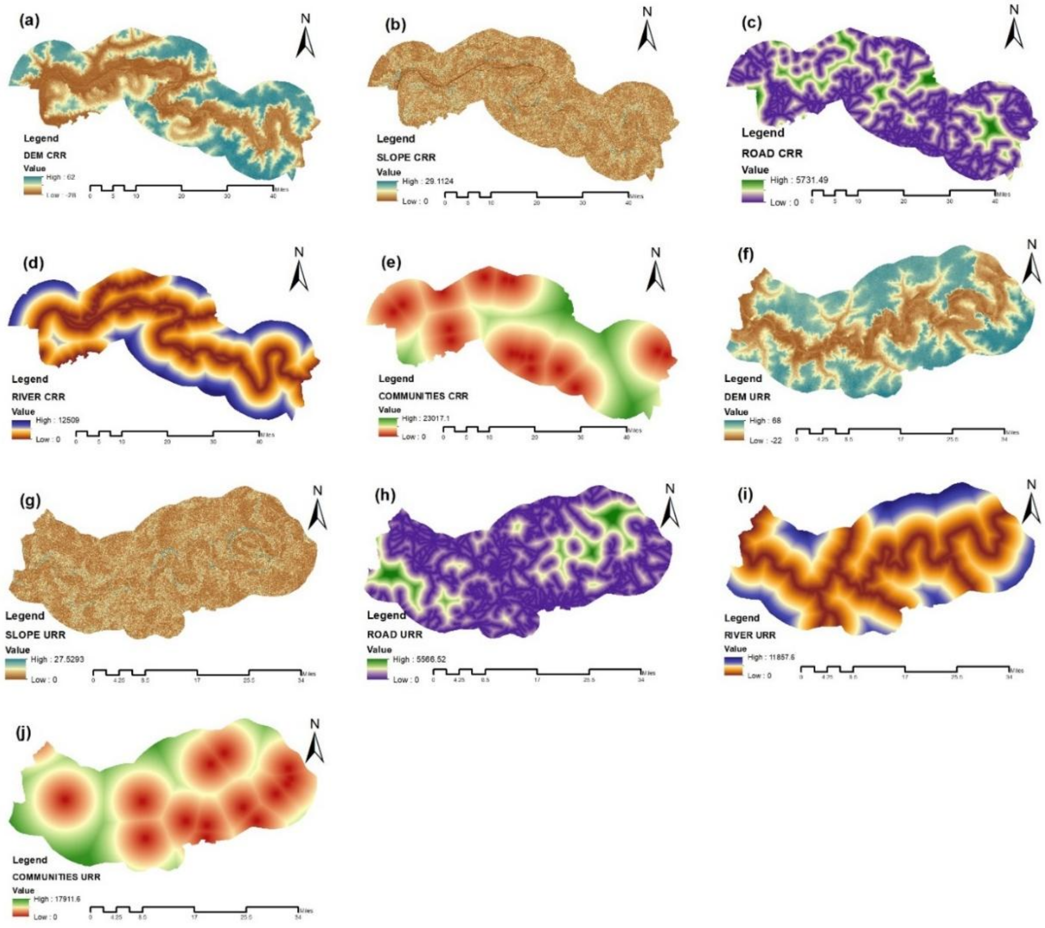

Figure A1: Spatial variables: (a) study area DEM CRR, (b) slope CRR, (c) proximity to roads CRR, (d) proximity to rivers CRR, (e) proximity to communities *CRR, (f) study area DEM URR, (g) slope URR, (h) proximity to roads URR, (i) proximity to rivers URR, (j) proximity to communities URR*