2026-03

Climate Variability, Community Perceptions, and the Mitigation Role of Church Forest Ecosystems across Agroecological Zones in Jabitehnan District, Northwest Ethiopia

Addisu, Bitew

BAHIR DAR UNIVERSITY

FACULTY OF SOCIAL SCIENCE

DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES

CLIMATE VARIABILITY, COMMUNITY PERCEPTIONS, AND THE MITIGATION ROLE OF CHURCH FOREST ECOSYSTEMS ACROSS AGROECOLOGICAL ZONES IN JABITEHNAN DISTRICT, NORTHWEST ETHIOPIA

BY: - ADDISU BITEW BIRHANIE

ADVISOR: - DANIEL AYALEW (PhD, ASSOCIATE PROFESSOR)

BAHIR DAR, ETHIOPIA

MARCH, 2026

CLIMATE VARIABILITY, COMMUNITY PERCEPTIONS, AND THE MITIGATION ROLE OF CHURCH FOREST ECOSYSTEMS ACROSS AGROECOLOGICAL ZONES IN JABITEHNAN DISTRICT, NORTHWEST ETHIOPIA

ETHIOPIA

ADDISU BITEW BIRHANIE

A DISSERTATION SUBMITTED TO THE DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES, FACULTY OF SOCIAL SCIENCES, BAHIR DAR UNIVERSITY IN FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN PHYSICAL GEOGRAPHY AND ENVIRONMENTAL STUDIES

ADVISOR:

DANIEL AYALEW (PhD, Associate Professor)

MARCH, 2026

BAHIR DAR, ETHIOPIA

Declaration

This is to certify that the thesis entitled **" Climate Variability, Community Perceptions, And The Mitigation Role Of Church Forest Ecosystems Across Agroecological Zones In Jabitehnan District, Northwest Ethiopia ",** submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in **physical geography and environmental studies** in the Department of Geography and Environmental Studies, Bahir Dar University, is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

Addisu Bitew Birhanie	_______________	25/03/2026
Name	Signature	Date

BAHIR DAR UNIVERSITY
POST GRADUATE STUDIES
FACULTY OF SOCIAL SCIENCES
DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES

Approval of Dissertation for defence

I hereby certify that I have supervised, read, and evaluated this dissertation titled **" Climate Variability, Community Perceptions, And The Mitigation Role Of Church Forest Ecosystems Across Agroecological Zones In Jabitehnan District, Northwest Ethiopia",** by Addisu Bitew Birhanie prepared under my guidance. I recommend the dissertation be submitted for oral defence (mock-viva and viva voce).

Daniel Ayalew (PhD, Associate professor)	____________	25/03/2026
Advisor's name	Signature	Date

BAHIR DAR UNIVERSITY
POST GRAGUATE STUDIES
FACULTY OF SOCIAL SCIENCES
DEPARTMENT OF GEOGRAPHY AND ENVIRONMENTAL STUDIES

Approval of Dissertation

We hereby certify that we have examined the dissertation entitled " **" Climate Variability, Community Perceptions, And The Mitigation Role Of Church Forest Ecosystems Across Agroecological Zones In Jabitehnan District, Northwest Ethiopia",** by Addisu Bitew Birhanie, and submitted in fulfilments for the requirements for the degree of Doctor of Philosophy in Physical Geography and Environment Studies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Board of Examiners

Asmamaw Alemu (PhD) ______ 24/06/2026
External examiner's name Signature Date

Amare Sewnet (prof) ______ 23/06/2026
Internal examiner's name Signature Date

Daniel Ayalew (PhD) ______ 23/06/2026
Advisor Signature Date

Dr. Mesfin Anteneh ______ 22/06/2026
Chair person's name Signature Date

Kassahun Gashu ______ 25 June 2026
Chair of Department or Graduate Program Coordinator Signature Date

Acknowledgement

I have received invaluable assistance from many individuals throughout the course of completing this thesis. I am pleased to take this opportunity to express my sincere gratitude and indebtedness to all of them.

First and foremost, I would like to convey my deepest appreciation to my advisor, Dr. Daniel Ayalew. His unwavering professional guidance, encouragement, and support were instrumental in the successful completion of this thesis. It was truly a privilege to have him as my supervisor. Without his continuous assistance and insightful feedback, this work would not have been realized. I am profoundly grateful for his dedication, timely support, and inspiring commitment, which have significantly contributed to my academic and professional development.

I would also like to extend my sincere gratitude to Debre Markos University and Bahir Dar University. Debre Markos University granted me study leave and financial support to pursue my PhD, while Bahir Dar University provided me with the opportunity to join the program and also supported my studies financially. I am particularly thankful to the staff of the Department of Geography and Environmental Studies at Bahir Dar University for their collegial support and for creating a conducive and supportive academic environment.

I also humbly acknowledge the invaluable cooperation of the local community, development agents, and officials at the Kebele, District, and Zonal levels. This study would not have been possible without their willingness to participate and provide the necessary information.

Furthermore, I wish to express my heartfelt gratitude to my family my wife, Fikir Alemu; my daughter, Afomiya Addisu; and my son, Sofoniyas Addisu for their constant encouragement, patience, and unwavering support throughout my study.

Above all, I thank God and His Mother, Saint Mary, for granting me the strength, courage, and perseverance to accomplish this work.

Table of Contents Page

List of Figures **Page**

List of Tables Page

List of Appendix **Page**

Abbreviations and acronyms

AGB	Above Ground Biomass
ACV	Average Conservation Value
BGB	Below Ground Biomass
CAGTB	Carbon Stock in Above Ground Tree Biomass
CBGB	Carbon Stock in Below Ground Tree Biomass
CBD	Convention for Biological Diversity
CV	Conservation Value
CCV	Cumulative Conservation Value
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
EOTC	Ethiopian Orthodox Tewahido Church
ETM+	Enhanced Thematic Mapper Plus
ESRI	Environmental Systems Research Institute
EVI	Enhanced Vegetation Index
FAO	Food and Agricultural Organization
FGD	Focus Group Discussion
GCP	Ground Control Point

GIS	Geographic Information System
GHGs	Greenhouse Gases
GPS	Ground Positioning System
LUCF	Land Use Change and Forestry
NDVI	Normalized Difference Vegetation Index
IPCC	Intergovernmental Panel on Climate Change
IDW	Inverse Distance Weighted
OLI	Operational Land Imager
RUSLE	Revised Universal Soil Loss Equation
RSR	Root Shoot Ratios
SOC	Soil Organic Content
SWAT	Soil & Water Assessment Tool
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
WRS	Worldwide Reference System
WBISPP	Woody Biomass Inventory and Strategic Planning Project

General Abstract

Climate variability and change pose significant challenges to agricultural production, ecosystem sustainability, and rural livelihoods in Ethiopia. Understanding climate trends, local perceptions, ecosystem resilience, and the climate mitigation potential of natural resources is essential for developing effective adaptation and mitigation strategies. This dissertation investigated climate variability, community perceptions, woody plant diversity, and the climate change mitigation potential of church forest ecosystems across agroecological zones in Jabitehinan District, Northwest Ethiopia. The study employed a mixed-methods research approach integrating meteorological, socioeconomic, ecological, and carbon stock data. Historical climate records from six meteorological stations obtained from the Ethiopian National Meteorological Agency were analyzed using the Mann–Kendall trend test, Sen's slope estimator, precipitation concentration index, and spatial interpolation techniques. Household survey data were collected from 361 farmers selected through a two-stage sampling procedure, complemented by key informant interviews and focus group discussions. Ecological data were gathered from four church forests distributed across semi-arid, sub-humid, and temperate-highland agroecological zones using systematically established vegetation plots. Woody species composition, diversity, structure, regeneration status, and carbon stock were assessed through field measurements and standard ecological and biomass estimation methods. The climate analysis revealed declining rainfall trends across seasons, with annual rainfall decreasing at a rate of 0.0122 mm, while mean annual temperature increased by 0.206°C. Maximum, minimum, and mean temperatures increased by 0.014°C, 0.029°C, and 0.037°C per decade, respectively. Spatial analysis showed considerable variation in rainfall distribution, with the highest annual rainfall occurring in the upper highlands. Farmers widely perceived declining and increasingly erratic rainfall, delayed onset and early cessation of rainy seasons, rising temperatures, and shifting planting periods. Perceptions varied significantly among agroecological zones, with semi-arid communities reporting stronger climate-related changes. Gender, education, access to irrigation, training opportunities, climate information, indigenous knowledge, and extension services significantly influenced climate change awareness. Ecological assessment identified 49 woody species belonging to 35 families across the three church forests. Fabaceae, Euphorbiaceae, Cupressaceae, and Oleaceae were the dominant families. Shannon–Wiener *diversity values ranged from 2.58 to 3.29, indicating moderate to high species diversity. Forest structural analysis showed dominance of individuals in lower height classes, while diameter class distributions varied among forests. Three church forests exhibited good regeneration status, whereas one showed fair regeneration, demonstrating the important role of church forests in conserving biodiversity and maintaining ecosystem integrity. Carbon stock assessment demonstrated significant variation among agroecological zones. Church forests in the semi-arid zone stored substantially higher carbon than those in the sub-humid and temperate-highland zones. Mean aboveground, belowground, and total carbon stocks across the study area were 33.4 t ha*$^{-1}$*, 8.3 t ha*$^{-1}$*, and 41.8 t ha*$^{-1}$*, respectively. Analysis of variance indicated significant differences in carbon storage among agroecological zones (*$F = 3.54$*,* $p < 0.033$*). These findings confirm that church forests contribute not only to biodiversity conservation but also to climate change mitigation through carbon sequestration. The study demonstrates that Jabitehinan District is experiencing noticeable climate variability characterized by declining rainfall and rising temperatures, which are widely recognized by local communities. At the same time, church forests serve as important ecological refuges that conserve woody plant diversity, support forest regeneration, and provide measurable carbon sequestration benefits. Strengthening climate-smart agricultural practices, enhancing climate information services, promoting environmental education, and supporting community-based conservation of church forests are essential for improving resilience and advancing sustainable climate adaptation and mitigation efforts in Northwest Ethiopia.*

Keywords: Climate variability, community perception, church forests, woody species diversity, carbon stock, climate change mitigation, agroecological zones

CHAPTER ONE

1.1 Introduction

Climate change is one of the most serious global challenges of the 21st century, driven primarily by rising concentrations of greenhouse gases from human activities such as burning of fossil fuels and deforestation, leading to increasing average global temperatures and more frequent extreme weather events (IPCC, 2022). According to the IPCC (2023), continued emissions are projected to raise global warming beyond 1.5 °C unless deep and rapid reductions occur, intensifying risks to ecosystems, human health, food and water security, and infrastructure worldwide. The World Health Organization reports that climate change already contributes to humanitarian emergencies such as heat waves, floods, droughts, and wildfires and that over 3.6 billion people live in areas highly susceptible to its impacts, with projected additional deaths from under nutrition, malaria, diarrhea, and heat stress between 2030 and 2050 if action is delayed (WHO, 2023).

Literatures underscore that climate change is not only an environmental issue but a fundamental threat to global health, development, and stability requiring urgent collective action at all levels. Independent analyses confirm that 2024 was the warmest year on record, with the highest global mean temperatures measured since 1850, reflecting an intensification of long-term warming trends linked to anthropogenic emissions (Rohde, 2025). In addition to temperature increases, peer-reviewed research highlights interconnected challenges such as changing precipitation patterns, glacier retreat, and complex atmospheric circulation shifts that affect global climate variability and extreme weather risks (Bhattacharjee *et al.*, 2024). These findings underscore the urgency of robust mitigation and adaptation strategies worldwide, as climate change not only compromises environmental stability but also poses escalating risks to human health, food systems, and socio-economic development across regions (WMO, 2025).

Climate change is profoundly affecting Africa, where rising temperatures, erratic rainfall, and extreme weather events are disrupting ecosystems, economies, and human well-being more intensely than in many other regions (Jones *et al.*, 2023). According to the World Meteorological Organization WMO (2025), Africa's average surface temperature in 2024 was approximately

0.86 °C above the 1991–2020 average, with parts of North Africa warming even faster, intensifying droughts, heat waves, floods, and water scarcity that jeopardize food security, health, and livelihoods across the continent. Despite contributing only a small fraction of global greenhouse gas emissions, African countries are bearing disproportionate climate impacts and adaptation costs, with the continent losing an estimated 2–5 % of GDP to climate extremes and requiring up to US $30–50 billion annually for adaptation efforts (WMO, 2025). These climatic shifts exacerbate hunger, displacement, and economic vulnerability, underlining the urgency for strengthened resilience and international support.

Forests are among the most important terrestrial ecosystems, providing a wide range of ecological, environmental, economic, and social services. They play a critical role in biodiversity conservation, carbon sequestration, climate regulation, watershed protection, nutrient cycling, and livelihood support for millions of people worldwide (FAO, 2020). However, global forest ecosystems are increasingly threatened by deforestation, habitat fragmentation, land-use change, and climate change, resulting in significant losses of biodiversity and ecosystem services (IPCC, 2022). In Ethiopia, extensive deforestation and agricultural expansion have reduced the country's natural forest cover considerably, leaving only fragmented remnants of the original Afromontane forests (Wassie *et al.*, 2010).

Among the remaining forest fragments in Ethiopia, the forests surrounding Ethiopian Orthodox Tewahedo Churches (EOTC) represent one of the most remarkable examples of indigenous and faith-based conservation systems. Church forests are sacred forest patches protected around churches and monasteries through religious beliefs and traditional conservation practices that have persisted for centuries (Aerts *et al.*, 2016). These forests are primarily found in the northern, central, and northwestern highlands of Ethiopia, where they often constitute the last remnants of native Afromontane vegetation within highly cultivated landscapes (Wassie *et al.*, 2010; Cardelús *et al.*, 2019).

Church forests play a vital role in conserving biodiversity. Numerous studies have reported that these sacred forests harbor a wide range of indigenous woody plant species, including many species that have become rare or locally extinct in surrounding agricultural areas (Wassie *et al.*, 2006b; Aerts *et al.*, 2016). As biodiversity refugia, church forests maintain genetic resources, support wildlife habitats, preserve ecosystem functions, and serve as important seed sources for landscape restoration (Cardelús *et al.*, 2012). Research conducted in different regions of Ethiopia has shown that church forests contribute significantly to the conservation of endemic and threatened plant species and enhance ecological connectivity in fragmented landscapes (Aerts *et al.*, 2016).

In addition to biodiversity conservation, church forests provide numerous ecosystem services. They regulate local microclimates, reduce soil erosion, improve water infiltration, enhance soil fertility, support pollinators, and contribute to watershed protection (Wassie *et al.*, 2010). Furthermore, church forests serve as important carbon sinks through the storage of carbon in woody biomass and forest soils. Studies have demonstrated that mature indigenous tree species found in church forests possess substantial carbon sequestration potential, contributing to climate change mitigation efforts (Dingamo *et al.*, 2021; Morka, 2025).

The conservation of church forests is strongly linked to the religious doctrines and cultural values of the Ethiopian Orthodox Tewahedo Church. Traditionally, local communities consider church compounds sacred spaces where tree cutting and other destructive activities are prohibited (Orlowska *et al.*, 2018). These religious beliefs have fostered long-term protection of forest resources and have enabled church forests to persist despite extensive environmental degradation in surrounding areas. Consequently, church forests represent a unique example of community-based natural resource management rooted in indigenous knowledge and spiritual values (Wassie *et al.*, 2010).

Community perceptions play a crucial role in the conservation and sustainable management of church forests. Previous studies have shown that local communities generally recognize church forests as important for biodiversity conservation, climate regulation, water protection, cultural heritage preservation, and spiritual values (Orlowska *et al.*, 2018). Communities often perceive these forests as sacred landscapes that contribute to environmental sustainability and local well-being. Such positive perceptions have historically enhanced community participation in conservation activities and strengthened local stewardship of forest resources (Aerts *et al.*, 2016).

Despite their ecological and cultural significance, church forests are increasingly threatened by various anthropogenic and environmental pressures. Population growth, agricultural expansion, settlement encroachment, fuel wood collection, livestock grazing, invasive species, and forest fragmentation have contributed to the degradation of many church forests across Ethiopia (Wassie *et al.*, 2010; Aerts *et al.*, 2016). As many church forests are relatively small and isolated, they are particularly vulnerable to edge effects, biodiversity loss, and ecological disturbances.

Climate change and climate variability have emerged as additional threats to church forest ecosystems. Ethiopia has experienced increasing temperatures, changing rainfall patterns, recurrent droughts, and more frequent extreme climatic events over recent decades (IPCC, 2022). These climatic changes can adversely affect forest structure, species composition, regeneration dynamics, and ecosystem functioning. Studies have reported that prolonged droughts and rainfall variability reduce seed germination, limit seedling establishment, increase tree mortality, and alter species distributions in Ethiopian forest ecosystems (Gebrehiwot *et al.*, 2021; Kindu *et al.*, 2022).

Church forests are particularly susceptible to climate-related disturbances because of their small size and fragmented nature. Small forest patches often possess lower ecological resilience and adaptive capacity than larger continuous forests, making them more vulnerable to climatic stressors (Aerts *et al.*, 2016). Rising temperatures and declining rainfall can increase moisture stress, reduce growth rates, and negatively affect natural regeneration processes. Furthermore, climate variability may intensify pest outbreaks, disease occurrence, and invasive species expansion, further threatening forest health and biodiversity (IPCC, 2022).

Climate variability also interacts with socio-economic pressures to exacerbate forest degradation. During periods of drought and crop failure, local communities may increase their dependence on church forests for fuel wood, grazing, and other livelihood resources, thereby increasing anthropogenic pressure on already vulnerable ecosystems (Gebrehiwot *et al.*, 2021). Such interactions between climatic and human-induced factors create complex challenges for the long-term conservation of church forests.

Recent studies have also indicated that socio-cultural transformations, modernization, and changing livelihood strategies may weaken traditional conservation mechanisms that have historically protected church forests (Orlowska *et al.*, 2018). As a result, some church forests are experiencing gradual declines in ecological integrity despite their sacred status. This situation highlights the need for integrated conservation strategies that combine traditional knowledge, community participation, scientific management, and climate adaptation measures.

Although considerable research has documented the biodiversity and ecological importance of church forests, limited attention has been given to understanding how local communities perceive the impacts of climate variability on these sacred forest ecosystems. Community perceptions are particularly important because local people are the primary custodians and beneficiaries of church forests. Their experiences and observations can provide valuable insights into climate-induced environmental changes, conservation challenges, and adaptation opportunities. Therefore, investigating the ecological condition of church forests alongside community perceptions of climate variability is essential for developing effective conservation and climate adaptation strategies. Such studies contribute to the broader understanding of the role of faith-based conservation systems in promoting biodiversity conservation, and climate change mitigation and adaptation in Ethiopia.

1.2 Statement of the Problem

Climate variability has become one of the most pressing environmental challenges affecting ecological systems and human livelihoods worldwide. Increasing temperatures, erratic rainfall patterns, recurrent droughts, and extreme weather events have altered ecosystem processes, biodiversity distribution, agricultural productivity, and rural livelihoods, particularly in developing countries that depend heavily on climate-sensitive natural resources (FAO, 2020; IPCC, 2022). Ethiopia is among the countries most vulnerable to climate variability due to its dependence on rain-fed agriculture, limited adaptive capacity, and extensive environmental degradation (Conway *et al.*, 2011; Ademe *et al.*, 2020).

Numerous studies conducted in Ethiopia have documented trends in rainfall variability, temperature changes, drought occurrence, and their impacts on agricultural production and food security (Belay *et al.*, 2017b; Abeje *et al.*, 2019; Alem *et al.*, 2022). However, most previous investigations have primarily focused on agricultural systems and household vulnerability, with relatively little attention given to the role of forest ecosystems in climate variability mitigation and adaptation (Aerts *et al.*, 2016; Mekonnen *et al.*, 2019). Forest ecosystems are increasingly recognized as critical components of climate change mitigation because they sequester atmospheric carbon, regulate local microclimates, conserve biodiversity, and enhance ecosystem resilience (Pan *et al.*, 2011a; IPCC, 2023). Understanding how forests respond to climate variability and contribute to mitigation efforts has therefore become an important scientific and policy priority.

In Ethiopia, centuries of deforestation and agricultural expansion have substantially reduced natural forest cover, leaving only fragmented forest remnants in many regions (Wassie *et al.*, 2010). Among these remnants, Ethiopian Orthodox Tewahedo Church forests represent unique socio-ecological systems that have been protected through religious and cultural traditions for centuries (Aerts *et al.*, 2016). These sacred forests conserve indigenous woody species, maintain ecological functions, and provide important ecosystem services to local communities (Cardelús *et al.*, 2013). Moreover, church forests constitute ideal ecological systems for assessing climate variability mitigation because they represent relatively undisturbed forest patches embedded within highly modified agricultural landscapes. Their long-term protection, indigenous species composition, and varying sizes across environmental gradients make them suitable natural laboratories for evaluating carbon sequestration potential, biodiversity conservation, and ecosystem resilience under changing climatic conditions (Wassie *et al.*, 2010; Aerts *et al.*, 2016).

Despite their ecological importance, significant knowledge gaps remain regarding the climate mitigation role of church forests. Most previous studies have concentrated on species composition, diversity, regeneration status, and forest structure (Eshete, 2007; Wassie *et al.*, 2010; Endalew *et al.*, 2020; Birhanu *et al.*, 2021). Only a limited number of studies have quantified biomass and carbon stocks in church forests, and these studies were generally conducted at individual sites without considering agroecological differences (Soromessa *et al.*, 2021). Consequently, there is insufficient empirical evidence regarding how carbon storage potential, forest structure, and ecological resilience vary among church forests located in different agroecological zones. This represents an important empirical gap because climatic conditions, vegetation characteristics, and ecological processes differ substantially across agroecological gradients.

Furthermore, previous climate variability studies have largely relied on meteorological records and remote sensing approaches, while local community perceptions have received comparatively limited attention (Belay *et al.*, 2017b; Alem *et al.*, 2022). Community perceptions are particularly important because local people directly experience climatic changes and often develop adaptation strategies based on indigenous knowledge and long-term environmental observations (Deressa *et al.*, 2011b). Existing studies examining farmers' perceptions of climate variability have generally focused on agricultural production systems and adaptation practices, with little consideration of how communities perceive the ecological functions and climate mitigation roles of church forests (Zerssa *et al.*, 2021; Teku, 2025). As a result, there is limited understanding of the relationship between local perceptions of climate variability and the ecological condition of culturally protected forest ecosystems.

Another important limitation in the existing literature is methodological. Most studies have examined climate variability, community perceptions, forest ecology, and carbon sequestration independently rather than integrating them within a single analytical framework. Consequently, the complex interactions among climatic variability, community responses, forest ecosystem dynamics, and climate mitigation functions remain poorly understood. Without such integration, it is difficult to determine whether local perceptions correspond with observed ecological changes or to identify how ecological conditions influence adaptation and conservation behaviours. Therefore, a methodological gap exists in the absence of interdisciplinary studies that simultaneously combine climate trend analysis, community perception assessment, forest ecological characterization, and carbon stock estimation.

The importance of agroecological variability further strengthens the need for an integrated assessment. Agroecological zones differ in rainfall amount, temperature regimes, soil characteristics, vegetation composition, and agricultural practices (Abeje *et al.*, 2019). These environmental differences influence both ecosystem responses to climate variability and human perceptions of climatic change. Communities residing in different agroecological zones may experience climate variability differently due to variations in resource availability, livelihood dependence, and exposure to climatic hazards. Similarly, church forests located in different agroecological settings may exhibit distinct species composition, regeneration patterns, biomass accumulation, and carbon sequestration capacities. However, little empirical evidence exists regarding how agroecological variability simultaneously shapes community perceptions and ecological responses within church forest ecosystems.

Jabitehnan District provides an appropriate setting for addressing these gaps because it encompasses diverse agroecological zones, experiences significant climate variability, and contains numerous church forests that serve as important ecological refugia within predominantly agricultural landscapes. Despite their ecological and cultural significance, no comprehensive study has simultaneously examined climate variability trends, community perceptions, forest ecological characteristics, and the climate mitigation role of church forests across agroecological zones in the district.

Therefore, this study was undertaken to address these empirical, methodological, and contextual gaps by integrating climate variability analysis, community perception assessment, woody species diversity and structure evaluation, regeneration analysis, and carbon stock estimation across church forests located in different agroecological zones of Jabitehnan District. By linking ecological measurements with local knowledge and climate data, the study provides a comprehensive understanding of how climate variability affects both human and ecological systems and how church forests contribute to climate change mitigation and ecosystem resilience. The findings are expected to generate scientific evidence that supports climate adaptation planning, forest conservation strategies, and sustainable management of culturally protected forest ecosystems in Ethiopia.

1.3 General Objective

The general objective of this study is to examine the spatiotemporal variability of climate factors, and assess the ecological responses to climate change, including farmers' awareness, church forest biodiversity and regeneration, and carbon sequestration potential across the agro-ecological zones of Jabitehinan District, Northwestern Ethiopia.

1.3.1 Specific Objectives

The specific objectives of this study are:-

- To investigate the spatiotemporal variability and trends of rainfall and temperature across agroecological zones of Jabitehinan District.
- To assess farmers' awareness and perceptions of climate change, and perceptions and determinants influencing these perceptions across agro-ecological zones in Jabitehinan District
- To assess species diversity and regeneration status of church forests along agro-ecological zones of Jabitehinan District
- To estimate the carbon sequestration potential of church forests and examine their implications for climate change mitigation in Jabitehinan District

1.4 Research Questions

- What are the spatiotemporal patterns, variability, and long-term trends of rainfall and temperature across the agro-ecological zones of Jabitehinan District?
- What are the key determinants influencing climate change awareness across different agro-ecological zones of Jabitehinan District?
- What is the species diversity and regeneration status of church forests across different agro-ecological zones in Jabitehinan District?
- What is the carbon sequestration potential of church forests, and how do they contribute to climate change mitigation in Jabitehinan District?

1.5 Significance of the study

This study provides farmers with evidence-based insights into long-term changes in rainfall and temperature patterns across different agro-ecological zones of Jabitehinan District. By linking scientific climate trend analysis with farmers' own perceptions, the findings enhance local understanding of climate variability and its impacts on agricultural productivity. The results can help farmers improve climate-smart decision-making, such as adjusting planting dates, crop choices, and soil and water conservation practices, thereby strengthening their adaptive capacity and livelihood resilience under changing climatic conditions.

For government administrators, the study offers spatially explicit and agro-ecology–specific climate information that supports evidence-based planning and resource allocation. The integration of climatic data, perception analysis, and ecosystem assessments provides a holistic framework for designing locally appropriate adaptation and mitigation strategies. The findings can inform district and regional development plans, agricultural extension programs, and environmental management initiatives aimed at reducing climate vulnerability and enhancing sustainable land use.

The study generates scientifically robust evidence on climate trends, farmers' adaptive perceptions, and the climate mitigation role of church forests. This information is valuable for shaping national and regional climate, agricultural, and forest policies, particularly those related to climate change adaptation, REDD+, and nature-based solutions. By highlighting the role of education, extension services, and climate information access in shaping farmers' perceptions, the study supports policies that prioritize knowledge dissemination, institutional capacity building, and inclusive climate governance.

The ecological and carbon stock assessments underscore the importance of church forests as reservoirs of biodiversity and significant carbon sinks. For church administrators, this study provides scientific justification for strengthening the protection and sustainable management of sacred forests. The findings can support awareness creation within religious institutions and communities, encouraging the integration of faith-based conservation practices with broader climate change mitigation and ecosystem restoration efforts.

NGOs working in climate adaptation, rural development, and natural resource management can use the study's findings to design context-specific interventions. The evidence on agro-ecological variation in climate impacts, perception, and forest carbon stocks enables NGOs to target vulnerable communities more effectively, promote climate-smart agriculture, and support community-based forest conservation initiatives, including those cantered on church forests.

For conservationists, the study highlights the ecological resilience and carbon sequestration potential of church forests within human-dominated landscapes. The documented species diversity, regeneration status, and carbon stocks provide a strong scientific basis for recognizing sacred forests as key conservation units. This contributes to broader conservation planning, biodiversity protection and ecosystem-based climate mitigation strategies in Ethiopia and similar regions.

Academically, the study contributes to the growing body of literature that integrates climate trend analysis, social perception studies, and ecosystem assessments within a single framework. It offers a methodological reference for interdisciplinary climate research in data-scarce regions and provides empirical evidence relevant to sub-humid and semi-arid agro-ecological zones in Ethiopia.

1.6 Scope of the study

The scope of the study is delimited based on three criteria: such as the objective that addressed, spatial and temporal delimitation. There were several issues that matter in the climate change and mitigation. Because each issue cannot be addressed in a single study, there was a need to delimit the scope of the present study. Accordingly, this study attempts to examine the spatiotemporal variability and trends of rainfall and temperature, perceptions and determinants of climate change awareness among farmers across agro-ecological zones, church forest species diversity and its regeneration status in different agro-ecological zones and Carbon sequestration potential of church forest and their implication for climate change mitigation. Geographically the study delimited to Jabitehinan administration district, the reason behind the selection of this study area is the presence of much church forest in closed and open canopy conditions, accessibility, peacefulness, and orderly situation of the study area. Temporally the study limited from 1981-2022 for meteorological data. The researcher selected 1981 as the starting year for rainfall and temperature trend analysis in the Jabitehinan District for the following key reasons: Data reliability and continuity, from 1981 onward, meteorological records in Ethiopia are generally more consistent, complete, and quality-controlled, reducing gaps and errors common in earlier datasets. Standard climatological baseline, the year 1981 marks the beginning of the 1981–2010 climatological normal periods, widely used by the World Meteorological Organization (WMO) for climate trend and anomaly analysis. Availability of gridded climate datasets, many high-resolution climate products commonly used in Ethiopian studies (e.g., satellite-based or reanalysis datasets) reliably begin in or around 1981. Adequate length for trend detection, starting in 1981 provides more than 30–40 years of data, which is statistically sufficient to detect long-term climate trends and variability.

1.7 Limitation of the study

This research is subject to several limitations that should be considered when interpreting its findings. First, the geographical coverage of the study area was relatively limited, which may not fully capture the spatial variability of climate patterns and ecosystem conditions across the wider region. As a result, the observed trends may not be entirely representative of neighbouring districts with different climatic and ecological contexts. Second, the political instability of the country highly affected psychologically and internet access for further works. Third, the study did not incorporate future climate change projections based on scenario modelling, such as those provided by CMIP or regional climate models. Consequently, while the research provides valuable insight into historical and current climate variability, it does not offer predictive assessments of future climate conditions, which are essential for long-term adaptation planning and policy formulation. Future studies should therefore consider expanding the spatial scope, and integrating scenario-based climate projections to strengthen the robustness of climate impact assessments for the region.

1.8 Organization of the study

This dissertation is presented in a monograph format and is organized into eight chapters. Chapter one provides a general introduction to the study, outlining its overarching concerns, objectives, significance, scope, limitations, and overall organization. Chapter Two presents a comprehensive review of the related literature, while Chapter Three describes the general methodology employed in the research. Chapter Four contains Article I, which examines the spatio-temporal variability of temperature and rainfall in the Jabitehinan District, Northwestern

Ethiopia. Chapter Five presents Article II, focusing on farmers' perceptions and the determinants of climate change awareness across different agro-ecological zones in the district. Chapter Six includes Article III, which assesses church forest species diversity and regeneration status across various agro-ecological zones of the Jabitehinan District. Chapter Seven features Article IV, addressing the carbon sequestration potential of church forests and their implications for climate change mitigation in the district. Finally, Chapter Eight provides a synthesis of the entire research, summarizes key findings, highlights the study's contributions, offers recommendations, and proposes directions for future research.

1.9 Key terms

Ethiopia traditionally classifies its environment into five agro-ecological zones mainly based on altitude, temperature, and rainfall. Below are the zones with their internationally recognized equivalent terms:

Traditional Ethiopian Zone	Altitude (m a.s.l.)	Climate Characteristics	International / Scientific Equivalent
Bereha	< 500 m	Very hot, arid, extremely low rainfall	Arid desert
Kolla	500–1,500 m	Hot to warm, low to moderate rainfall	semi-arid
Woina Dega	1,500–2,300 m	Mild temperature, moderate rainfall	Sub-humid
Dega	2,300–3,200 m	Cool temperature, relatively high rainfall	Temperate highland
Wurch	> 3,200 m	Very cold, frost common	Afro-alpine / Alpine tundra

Source: FAO (1996), Agro-ecological Zoning: Guidelines FAO Soils Bulletin No. 73, Rome.

CHAPTER TWO

REVIEW LITERATURE

2.1 The Concept of Climate Change and Variability

According to the definition of the Intergovernmental Panel on Climate Change IPCC (2007), climate change is "any change in climate over time, whether due to natural variability or as a result of human activity." IPCC (2014a) has further given a more elaborated definition to climate change stating that climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." Both definitions acknowledged that climate change is attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. Climate change also embraces the observed and projected rise in average global temperature, and the related impacts, including: an increase in severe weather incidents; glaciers and sea level rise, melting of icebergs, and changes in the timing and amount of rainfall (CARE International Poverty *et al.*, 2011).

Climate variability is defined as the natural fluctuation of climate conditions over time, including changes in temperature, precipitation, and other atmospheric variables at regional and global scales(IPCC, 2021). These variations occur across multiple temporal scales ranging from seasonal and interannual to decadal and represent an intrinsic feature of the Earth's climate system rather than a permanent alteration in climate state(WMO, 2025). It is typically quantified by analyzing deviations from long-term climatic averages (climate normal) using statistical measures such as anomalies and variability indices. Thus, climate variability illustrates the dynamic and ever-changing nature of the climate system, even in the absence of long-term climate change trends (IPCC, 2021; WMO, 2025).

Recent literature indicates that climate variability is influenced by both internal dynamics of the climate system and external natural forcing mechanisms(Jones *et al.*, 2023). Key drivers include ocean–atmosphere interactions such as the El Niño–Southern Oscillation (ENSO) and large-scale atmospheric circulation systems like the Intertropical Convergence Zone (ITCZ), which play a critical role in shaping rainfall and temperature patterns, particularly in regions such as Ethiopia(IPCC, 2022). These processes often result in irregular rainfall distribution, drought occurrences, and temperature anomalies across different years. While climate variability is a natural phenomenon, emerging evidence suggests that anthropogenic climate change is amplifying its intensity and frequency, thereby increasing the likelihood of extreme weather events and exacerbating impacts on ecosystems and human livelihoods(NOAA, 2025).

Emissions of greenhouse gases, such as carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) that are warming the planet, affect the earth's climate. Most of the warming is driven by increasing atmospheric concentrations of CO_2 released by burning fossil fuels (IPCC, 2014a). The economy of developing nations will be more affected by climate change, partly due to their greater exposure to climate shocks and also because of their limited adaptive capacity. However, no country is immune (UNDP, 2007a) and of the developing countries, many in Africa are seen as being the most vulnerable to climate variability and change (UNDP, 2007a). Poor agricultural productivity is one of many factors driving vulnerability of developing countries. Climate change will create large incremental risks (UNDP, 2007a) and a small incremental risk of more droughts can lead to large human development setbacks.

2.2 Manifestations of climate change and variability

Knowledge on how climate change is manifested has a paramount importance to understand its impact on different sectors and devise timely viable measure to minimize the impact. The major manifestations of climate change are increase in average temperature of the planet and change in hydrological cycle (Lovejoy *et al.*, 2005). The main characteristics of climate change according to the UNFCCC (2007a), are increases in average global temperature; changes in cloud cover and precipitation; melting of ice caps and glaciers and reduced snow cover; and increases in ocean temperatures and ocean acidity due to seawater absorbing heat and carbon dioxide from the atmosphere. Increasing food insecurity, water scarcity, drought, spread of diseases to new areas, damage from floods and forced migration due to desertification of previously arable land or sea level rise are some of the likely climate change-induced events in developing countries including Africa (Solomon *et al.*, 2007). Africa is particularly vulnerable to such climate change-induced hazards because of multiple stresses and low adaptive capacities, arising from endemic poverty, weak institutions, and complex disasters and associated conflicts. Drought will continue to be a primary concern for many African populations. The frequency of weather- and climate-related disasters has increased since the 1970s, and the Sahel and Southern Africa have become drier during the twentieth century. Water supplies and agricultural production will become even more severely diminished. By 2020, in some African countries agricultural yields could be reduced by as much as 50%; whereas by the 2080s, the area of arid and semi-arid land in Africa will likely increase by 5-8 % (IPCC, 2007).

In Ethiopia, drought and flood are major manifestations of climate change. In the past few years for instance, the rainfall pattern has shown a decreasing trend in amount and distribution (Alemu, 2019). Moreover recurrent droughts and floods in Ethiopia are definitive sign that climate change is indeed impacting on Ethiopia. Late start and early cessation of the main rainy season are frequently observed in the rainfall regime in the past few years (Alemayehu, 2022).

Climate variability manifests across multiple environmental, economic, and social sectors, significantly influencing natural systems and human livelihoods. One of the most affected sectors is agriculture, particularly in developing countries such as Ethiopia, where farming is largely rain-fed. Variations in rainfall patterns, increasing temperatures, and the frequency of extreme events such as droughts and floods have led to reduced crop productivity, shifting growing seasons, and declining soil moisture. Recent studies indicate that climate variability contributes to changes in crop suitability, phenology, and yield reduction, ultimately threatening food security (Sinore *et al.*, 2024; Abebaw, 2025). In Ethiopia, for example, increasing temperature trends and erratic rainfall have been associated with recurrent droughts and reduced agricultural output, affecting rural livelihoods and increasing vulnerability among farming communities (Ademe *et al.*, 2020). Additionally, climate variability exacerbates pest infestations and livestock diseases, further reducing agricultural resilience and productivity (Ahmed *et al.*, 2014b). These manifestations highlight the sensitivity of agricultural systems to climate fluctuations and the urgent need for adaptive strategies.

Another critical area where climate variability is evident is water resources. Variability in precipitation patterns, coupled with rising temperatures, has significantly altered the hydrological cycle, leading to increased frequency of droughts, reduced river flows, and declining groundwater levels (WMO, 2025). Recent global evidence shows that extreme heat and prolonged drought conditions have caused record-low river flows, threatening water availability for agriculture, industry, and domestic use(IPCC, 2023). Furthermore, glacier retreat and reduced snowfall are diminishing freshwater supplies for billions of people, particularly in regions dependent on mountain water systems. These changes not only reduce water availability but also increase the risk of floods and water-related disasters due to irregular rainfall distribution. In agricultural contexts, increased evapotranspiration driven by rising temperatures has led to higher water demand for crops, intensifying water scarcity challenges (Peña-Guerrero *et al.*, 2026). Thus, climate variability significantly disrupts water resource availability, posing a major threat to sustainable development.

The health sector is also increasingly affected by climate variability through both direct and indirect pathways. Changes in temperature and precipitation patterns influence the distribution and transmission of climate-sensitive diseases such as malaria, dengue, and waterborne infections (Aniye *et al.*, 2025). Extreme weather events, including heat waves and floods, can lead to increased mortality, malnutrition, and displacement of populations (WHO, 2023). In many developing regions, climate variability has contributed to food shortages, reduced access to clean water, and increased exposure to health risks, thereby weakening community resilience (Viste *et al.*, 2013). Moreover, rising temperatures and heat stress have been linked to adverse health outcomes, particularly among vulnerable populations such as children, the elderly, and those with pre-existing conditions. These impacts demonstrate the complex interaction between climate variability and public health systems.

Climate variability also manifests strongly in the energy sector, particularly in countries that rely heavily on hydropower (Marzouk, 2025). Variability in rainfall and prolonged drought conditions reduce water levels in reservoirs, thereby decreasing electricity generation capacity (IPCC, 2021). For instance, severe drought has disrupted hydropower production in several countries, leading to energy shortages and economic losses (Tsiftsi Athanasiou, 2025). This highlights the vulnerability of energy systems to climatic fluctuations and the need for diversification of energy sources. Similarly, increased temperatures can raise energy demand for cooling, further straining energy infrastructure and supply systems. The interplay between climate variability and energy production underscores the importance of integrating climate resilience into energy planning.

In addition, ecosystems and biodiversity are highly sensitive to climate variability. Changes in temperature and precipitation patterns affect species distribution, ecosystem productivity, and ecological balance (IPCC, 2022). Frequent droughts, floods, and temperature extremes can lead to habitat degradation, loss of biodiversity, and disruption of ecosystem services such as carbon sequestration and water regulation (UNEP, 2021). In many regions, climate variability has contributed to land degradation, soil erosion, and reduced vegetation cover, which in turn affect agricultural productivity and environmental sustainability (MillenniumEcosystemAssessment, 2003). These ecological impacts are particularly pronounced in fragile ecosystems such as dry lands and forest systems, where even small climatic changes can have significant consequences.

Climate variability has profound socio-economic implications, particularly in vulnerable communities. It contributes to income instability, food insecurity, migration, and conflict over natural resources such as water and land (UNDP, 2007b; UNMigration, 2023). In regions dependent on climate-sensitive livelihoods, such as agriculture and pastoralism, variability in climate conditions can lead to loss of income and increased poverty levels (AfricanDevelopmentBank, 2024). Studies have shown that climate variability is a major driver of rural-to-urban migration, as households seek alternative livelihoods in response to declining agricultural productivity (UNICEF, 2023). Furthermore, it exacerbates existing inequalities by disproportionately affecting marginalized populations with limited adaptive capacity. These socio-economic manifestations highlight the need for integrated policies and adaptive strategies to mitigate the impacts of climate variability.

2.3 Projected climate change in the Globe, Africa and Ethiopia

Projected climate change at the global scale indicates a continued rise in temperature, intensification of extreme weather events, and significant alterations in atmospheric and oceanic systems throughout the 21st century. According to the Intergovernmental Panel on Climate

Change (IPCC, 2021), global surface temperature is expected to increase by approximately 1.5°C to over 3°C by the end of the century, depending on greenhouse gas emission scenarios. Recent projections based on CMIP6 climate models suggest that the 1.5°C threshold could be reached as early as the late 2020s, with higher warming levels likely under high-emission pathways (Forster *et al.*, 2025). These projections highlight the urgency of mitigation efforts, as even small increases in global temperature are associated with disproportionately large impacts on natural and human systems.

In addition to temperature rise, projected global climate change is characterized by significant shifts in precipitation patterns and hydrological cycles(WMO, 2025). Some regions are expected to experience increased rainfall and flooding, while others will face intensified drought conditions due to changes in atmospheric circulation and evapotranspiration rates. Climate models indicate that up to 74% of drought-prone regions could experience severe water scarcity events by the end of the century if emissions remain high(Lee *et al.*, 2021). Furthermore, global precipitation variability is projected to increase, with more intense and frequent extreme rainfall events in tropical and high-latitude regions. These changes are closely linked to large-scale processes such as the weakening of ocean circulation systems, including the Atlantic Meridional Overturning Circulation (AMOC), which influences global climate patterns and rainfall distribution.

Sea-level rise is another major component of projected global climate change, driven primarily by thermal expansion of oceans and melting of glaciers and ice sheets. By 2100, global sea levels are projected to rise significantly, increasing the risk of coastal flooding, erosion, and displacement of populations (Gebresellase *et al.*, 2025). Projections indicate that millions of people living in low-lying coastal areas will be exposed to increased flooding risks, particularly in developing regions (Tsiftsi Athanasiou, 2025). In addition, warming oceans and increasing atmospheric temperatures are expected to trigger ecological tipping points, such as coral reef degradation and loss of biodiversity, further threatening global ecosystems (IPCC, 2021).

Another important aspect of projected global climate change is the increase in the frequency and intensity of extreme events (IPCC, 2022). Heat waves, storms, wildfires, and heavy rainfall events are expected to become more severe and frequent under continued warming (Forster *et* *al.*, 2025). For example, heat extremes that previously occurred once in 50 years are projected to occur much more frequently in a warmer climate, significantly affecting human health, agriculture, and infrastructure (Gebresellase *et al.*, 2025). Moreover, global warming is not uniform; regions such as the Arctic are projected to warm at rates significantly higher than the global average, leading to accelerated ice melt and feedback effects that further amplify global climate change (IPCC, 2021).

Projected climate change in Africa indicates that the continent will experience some of the most severe impacts of global warming due to its high vulnerability and limited adaptive capacity. According to the (IPCC, 2022), Africa is projected to experience faster-than-global-average warming in many regions, with temperature increases ranging from 2°C to over 5°C by the end of the century under high-emission scenarios. Recent observations already show significant warming trends, with Africa's average temperature rising above historical baselines and extreme heat events becoming more frequent (WMO, 2025). These temperature increases are expected to exacerbate existing environmental and socio-economic challenges across the continent(IPCC, 2022).

Rainfall patterns in Africa are projected to become increasingly variable and unpredictable, with some regions experiencing increased precipitation while others face prolonged droughts. For instance, Southern Africa is projected to become significantly drier, making it one of the most vulnerable regions to water scarcity in the future (Munday *et al.*, 2025). In contrast, parts of East and West Africa may experience more intense rainfall events, increasing the risk of flooding and associated disasters (Balogh *et al.*, 2020). These changes in precipitation patterns are expected to disrupt agricultural systems, reduce water availability, and increase the frequency of extreme weather events such as droughts and floods.

Hydrological projections further indicate that climate change will significantly affect water resources across Africa (Denison *et al.*, 2024). Studies using advanced climate models show that river flows and stream flow extremes will change substantially, with increased variability and more frequent extreme events in basins such as the Upper Awash in Ethiopia (Gebresellase *et al.*, 2025). Additionally, increasing temperatures will enhance evapotranspiration rates, further reducing water availability in already water-stressed regions (IPCC, 2022). These changes are expected to have severe implications for agriculture, hydropower generation, and domestic water supply.

Climate change is also projected to have significant impacts on ecosystems and biodiversity in Africa. Changes in temperature and precipitation will alter species distribution, ecosystem productivity, and ecological balance (Munday *et al.*, 2025). Fragile ecosystems such as dry lands, savannahs, and forests are particularly vulnerable, with increased risks of land degradation, desertification, and biodiversity loss (Dioha *et al.*, 2026). Moreover, climate-induced changes in vegetation and land cover may further exacerbate environmental degradation and reduce ecosystem services essential for human well-being (Gebresellase *et al.*, 2025).

The socio-economic impacts of projected climate change in Africa are expected to be profound. The continent is projected to host a growing share of the global population exposed to climate risks, particularly under higher warming scenarios (Dioha *et al.*, 2026). Climate change is expected to exacerbate poverty, food insecurity, and health challenges, while also increasing the likelihood of migration and conflict over scarce resources (Gebresellase *et al.*, 2025). Reports indicate that climate-related disasters are already causing significant economic losses, with some African countries losing up to 2–5% of their GDP annually due to climate impacts (IPCC, 2022). Furthermore, Africa faces a substantial climate finance gap, limiting its ability to effectively adapt to these projected changes.

The models predicting future climate change scenario in Ethiopia put conclusion that temperature will increase in the coming decades. However, there is conflicting results concerning the predicted level of rainfall (Ferede *et al.*, 2013). There are constant, decreasing and increasing levels of projected rainfall levels which were generated using different models. According to Mahoo et al. (2013), the frequency and severity of natural shocks in Ethiopia is increasing because of severe and repeated rainfall failures which strengthens the scenario that rainfall is decreasing time to time. According to (Alemayehu, 2022) the annual temperature of the suha watershed in upper Blue Nile showed a slightly increasing trend, in which the magnitude is quite different from the rainfall. It is low at the beginning and slightly increased toward the end of the projection period (2021–2040). On average, the temperature increases by about 0.307 °C during the projection period. According IPCC (2014a) temperature will increase in the range of 1.7-

2.10C by the year 2050 and 2.7-3.40C by the year 2080 over Ethiopia. The country will experience an increasing level of temperature and rainfall in the coming decades. However, it stated that a small increase in rainfall can be expected.

Overall, projected climate change at both global and regional scales presents complex and interconnected challenges, including environmental degradation, economic losses, and social disruptions. In Africa, these challenges are particularly severe across key sectors such as agriculture, water resources, ecosystems, and socio-economic systems, reflecting the continent's high vulnerability and limited adaptive capacity. The magnitude and distribution of these impacts will largely depend on future emission pathways as well as the effectiveness of mitigation and adaptation strategies implemented at global, regional, and national levels. Therefore, there is an urgent need for targeted adaptation measures, increased investment in climate resilience, and strengthened international support to address the disproportionate burden faced by vulnerable regions, particularly Africa.

2.4 Climate change impact

Climate change exerts multiple stresses on the biological, physical, social and institutional environments that affect agricultural production (Asrat *et al.*, 2018). Its impacts disproportionately affected Sub-Saharan African countries including Ethiopia because of the higher dependency of their economies on climate-sensitive activities such as rain-fed agriculture (Belay *et al.*, 2017a). Some of the induced changes are expected to be immediate, while others involve gradual shifts in temperature, vegetation cover and species distributions. Climate change is expected to and in parts of Africa has already begun to alter the dynamics of drought, rainfall and heat waves, and trigger secondary stresses such as the spread of pests, increased competition for resources, and biodiversity losses (Christensen *et al.*, 2007).

Climate change is one of the most pressing global challenges of the 21st century, affecting natural and human systems across multiple sectors. It is primarily driven by anthropogenic greenhouse gas emissions, which have led to rising global temperatures, altered precipitation patterns, and increased frequency of extreme weather events (IPCC, 2022). These changes are not isolated but rather interconnected, affecting agriculture, water resources, health, ecosystems, infrastructure, and socio-economic systems. The impacts are particularly severe in developing regions such as Africa, where adaptive capacity is limited and livelihoods are highly climate-sensitive. Understanding sector-specific impacts is essential for designing effective adaptation and mitigation strategies.

Agriculture is one of the most climate-sensitive sectors and is directly affected by changes in temperature, precipitation, and extreme weather events. Climate change alters crop phenology, reduces yields, and increases the risk of crop failure (FAO, 2021). Recent studies show that rising temperatures and erratic rainfall significantly reduce agricultural productivity, particularly in rain-fed systems (Balogh *et al.*, 2020). For example, global crop yields, including wheat and maize, are projected to decline under high-emission scenarios due to heat stress and water scarcity (IPCC, 2022).

In Africa, agriculture is highly vulnerable because it depends heavily on rainfall. Climate variability and change have been shown to negatively affect crop productivity and food security by altering growing seasons and increasing drought frequency (Sinore *et al.*, 2024). Similarly, in Ethiopia, major crops such as barley, wheat, maize, and sorghum are highly sensitive to climatic fluctuations, resulting in reduced yields and increased food insecurity (Gebresellase *et al.*, 2025). Climate change also affects livestock through heat stress, reduced pasture availability, and increased disease prevalence. These impacts threaten rural livelihoods, increase poverty, and undermine food systems globally.

Water resources are significantly affected by climate change through changes in precipitation patterns, increased evaporation, and altered hydrological cycles. Rising temperatures increase evapotranspiration, reducing soil moisture and water availability. At the same time, changes in rainfall patterns lead to increased droughts in some regions and flooding in others (WMO, 2025). Recent evidence indicates that freshwater availability is becoming more variable, with increased risks of water scarcity in already stressed regions (Abebaw, 2025). Climate change affects river flows, groundwater recharge, and reservoir levels, thereby impacting water supply for agriculture, industry, and domestic use (IPCC, 2022). In Africa, hydrological systems such as the Upper Awash Basin in Ethiopia are projected to experience increased variability in stream flow and more frequent extreme hydrological events (Gebresellase *et al.*, 2025). Reduced water availability also affects hydropower generation, irrigation systems, and urban water supply, making water management a critical challenge under climate change.

Climate change poses serious risks to human health through both direct and indirect pathways. Direct impacts include heat stress, heat waves, and mortality associated with extreme temperatures. Indirect impacts arise from changes in the distribution of vector-borne diseases, waterborne diseases, and food insecurity. Recent reports indicate that climate change is already contributing to increased heat-related deaths and disease outbreaks worldwide (WHO, 2023). Rising temperatures expand the geographical range of diseases such as malaria and dengue fever, exposing new populations to health risks. Climate-related disasters such as floods and droughts also contribute to malnutrition, displacement, and mental health challenges (IPCC, 2022). Furthermore, water scarcity and poor sanitation increase the risk of waterborne diseases, particularly in developing countries. Vulnerable populations, including children, the elderly and low-income communities, are disproportionately affected. Climate change is therefore a major threat to global public health systems and requires urgent adaptation measures, including strengthening health infrastructure and early warning systems.

Ecosystems and biodiversity are highly sensitive to climate change, as changes in temperature and precipitation affect species distribution, ecosystem functioning, and ecological balance(IPCC, 2022). Climate change is a major driver of biodiversity loss, as many species are unable to adapt quickly to changing environmental conditions (MEA, 2003). Recent research shows that climate change leads to habitat degradation, species migration, and increased extinction risks (Díaz *et al.*, 2019). Rising temperatures and changing rainfall patterns affect ecosystem productivity and reduce carbon sequestration capacity. Ecosystems such as forests, wetlands, and dry lands are particularly vulnerable to climate stress (UNDP, 2007b). In addition, climate change contributes to land degradation, soil erosion, and desertification, especially in arid and semi-arid regions. These changes reduce vegetation cover and disrupt ecosystem services such as water regulation, soil fertility, and climate regulation(UNICEF, 2023). Loss of biodiversity also affects ecosystem resilience, making ecosystems more vulnerable to future climate impacts (Díaz *et al.*, 2019). Therefore, protecting ecosystems is essential for maintaining environmental sustainability and supporting human livelihoods.

The energy sector is both a contributor to and a victim of climate change. Climate variability affects energy production, distribution, and consumption. Hydropower, which is highly dependent on water availability, is particularly vulnerable to changes in precipitation and drought conditions. Climate change reduces water levels in reservoirs, leading to decreased electricity generation capacity. At the same time, increased temperatures raise energy demand for cooling, placing additional stress on energy systems. According to recent assessments, climate-related impacts on water availability directly affect energy production, especially in hydropower-dependent regions (IPCC, 2022).

Extreme weather events such as storms, floods, and heat waves can damage energy infrastructure, including power plants, transmission lines, and distribution networks (Janjic, 2025). These disruptions lead to power outages and economic losses (Alba *et al.*, 2023). To address these challenges, there is a need to diversify energy sources by investing in renewable energy technologies such as solar and wind power, which are less vulnerable to climate variability (IPCC, 2022). Climate change also affects infrastructure and urban systems through increased exposure to extreme weather events (UNEP, 2021). Floods, storms, and heat waves can damage roads, buildings, bridges, and communication systems (Sinore *et al.*, 2024). Urban areas are particularly vulnerable due to high population density and inadequate infrastructure. Rising sea levels pose a significant threat to coastal cities, increasing the risk of flooding, erosion, and displacement (UNICEF, 2023). Additionally, heat waves in urban areas contribute to the “urban heat island” effect, increasing energy demand and health risks (UNEP, 2021). Infrastructure damage due to climate change leads to economic losses and disrupts essential services such as transportation, water supply, and electricity.

Urban planning must incorporate climate resilience measures, including improved drainage systems, green infrastructure, and climate-resilient building designs. Integrating climate considerations into urban development is essential for reducing vulnerability and enhancing adaptive capacity.

Climate change has profound socio-economic implications, particularly in developing countries. It contributes to income instability, poverty, migration, and inequality. Climate-sensitive sectors such as agriculture and fisheries are major sources of livelihood for millions of people, and climate variability directly affects their productivity and income. Recent studies show that climate change exacerbates poverty by reducing agricultural productivity and increasing food prices (Ndondo, 2023). It also drives migration, as people move from rural to urban areas in search of better opportunities. Climate-induced resource scarcity can also lead to conflicts over water and land resources. Moreover, climate change disproportionately affects vulnerable populations, including women, children, and marginalized communities. These groups often have limited access to resources and adaptive capacity, making them more susceptible to climate risks (UNMigration, 2023). Addressing these challenges requires inclusive policies, social protection programs, and international cooperation.

Climate change impacts are widespread and affect multiple sectors simultaneously, including agriculture, water resources, health, ecosystems, energy, infrastructure, and socio-economic systems. These impacts are interconnected and often reinforce each other, increasing overall vulnerability. The severity of these impacts depends on the magnitude of future climate change and the effectiveness of adaptation and mitigation strategies. Therefore, urgent and coordinated global action is required to reduce greenhouse gas emissions, enhance resilience, and support vulnerable communities in adapting to a changing climate.

2.5 Climate change perception

In agrarian communities, the linkage between agriculture and climate is much more complex than others, and farmers are able to identify specific and important weather patterns. Farmers usually base their crop and other production decisions using local knowledge systems which are developed from years of observations and experiences. Local knowledge forecasts provide more than just information about the forecast. They provide a set of behavioural rules that households and communities follow when certain indicators are or are not observed. Predicting climate is also an important cultural component for farmers (Noor *et al.*, 1992).

According to Maddison (2007), perceiving change and then deciding whether or not to adopt a particular measure is process in climate change adaptation. Whenever they have the opportunity, farmers tend to adopt new variety of measures or technologies in response to the perceived changes of weather conditions. The supports from extension workers, information gained and technologies available to them will highly influence their adaptation and response capacity. For instance, farmers use water conservation techniques whenever the rainfall patterns are changed and amounts of rain are reduced. They tend to plant different crop varieties and use short term crops with adjustment of planting dates. These adjustments are done when they perceive reduction in rainfall and changes in the onset and offset of rainy seasons.

The study by Fosu-Mensah *et al.* (2012a) showed that farmers are well aware of climate change, but few seem to actively take steps toward adjusting their farming activities. According to Deressa *et al.* (2011a), majority of farmers were able to recognize that temperatures have increased and there has been a reduction in the volume of rainfall, still few farmers lack the perception of change in climatic condition of their area to take steps to adjust their farming activities. The degree of farmer's perception on climate change also depends on its impact on farmer's livelihood, their social, institutional and economic background. It is different and depends mainly on level of education, livelihood activity, location and age.

2.6 Carbon sequestration potential of forests

Global warming is incontrovertibly one of the main environmental issues of this century. This phenomenon is having adverse impacts on the global climate through increases in the temperature of the earth. This phenomenon is caused mainly by the increase in atmospheric concentrations of greenhouse gases (GHGs) (IPCC, 2007), the most common of which is carbon dioxide (CO2). In 2012 global CO2 emissions recorded were 34.5 billion tonnes (UNFCCC, 2015a). The rates of emissions of CO2 continue to surge, with increased concentrations reaching their fastest rate for 30 years in 2013, regardless of the warnings given by the world's scientists to reduce emissions in order to stop increases in global temperatures. The experts gave strong warnings that the world was "running out of time" to reverse the escalating levels of CO2 to solve the climate change problems. According to the IPCC's Fifth Assessment Report UNFCCC

(2015a) between the period 1970 - 2010 total anthropogenic emissions have been on the increase; greater absolute increases having occurred between 2000 and 2010 with estimated anthropogenic emissions in 2010 reaching 49 ± 4.5 GtCO2-eq yr-1. In order to reduce the GHGs in the atmosphere, two key activities are relevant (UNFCCC, 2015a): reduce the anthropogenic emissions of CO2, and create or promote carbon sinks in the biosphere. The second option proposes storing atmospheric C in the biosphere, and in that regard, land-use systems such as agroforestry are of considerable importance (Saha *et al.*, 2009).

Forests provide climate change mitigation and adaptation, hydrological services, help in agricultural productivity, combat erosion, and improve wildlife habitat and wood or availability of other forest resources. Hence, losses and degradation of forest can result in impacts like floods and landslides, on the local environment, as well as wider impacts such as global climate change (Sukhdev *et al.*, 2010). Forests, thus, play a key role in climate change through global carbon cycle due to the large amount of carbon they are able to store in vegetation and soils (Pan *et al.*, 2011b) and (IPCC, 2003). Furthermore, trees are able to exchange large amounts of CO2 with the atmosphere through natural processes and biotic and abiotic disturbances. They serve as sources of carbon by releasing CO2 and non-CO2 gases to the atmosphere, once total respiration or oxidation of plants, soil and dead organic matter go beyond net primary productivity. Trees can also function as carbon sinks and absorb CO2 from the atmosphere when agricultural land and pastures are left to fallow and convert to forests, or are returned to forests or plantations by enrichment planting of forests (IPCC, 2003).

2.6.1 Carbon dioxide exchange between Terrestrial Vegetation and the Atmosphere

Organic chemicals are characterized by their carbon chains that along with oxygen and hydrogen form their main contents, with smaller additions of nitrogen and sulphur and some metals. However, life can be said to be dominated by the carbon cycle. In the exchange of carbon dioxide (CO2) between terrestrial vegetation and the atmosphere, with net accumulation followed by carbon (C) release, the net balance between sequestration and release shifts from minute-to-minute (for example, with cloud interception of sunlight), to a day-night pattern, across a seasonal cycle of dominance of growth and decomposition, through decadal patterns of build-up of woody vegetation or century-scale build-up of peat soils out to the stages of the lifecycle of a vegetation or land use system. During daytime in the growing season, plants capture CO2 from the atmosphere and bind the carbon atoms together to form sugars, releasing oxygen (O2) in the process. At night time and at times those plants don't have active green leaves; the reverse process of 'respiration' dominates(Assefa *et al.*, 2013).

2.6.2 Build-up of Carbon in Woody Vegetation

The build-up of carbon in woody vegetation is a central component of the global carbon cycle and plays a critical role in climate change mitigation. Woody vegetation including trees, shrubs, and forest biomass acts as a major carbon sinks by absorbing atmospheric carbon dioxide (CO_2) through photosynthesis and storing it in biomass and soils (IPCC, 2021). This process is fundamental to regulating atmospheric CO_2 concentrations and, consequently, global climate systems.

Woody plants accumulate carbon primarily in their above-ground biomass (trunks, branches, and leaves) and below-ground biomass (roots) (Jose, 2009). Through photosynthesis, plants convert CO_2 into organic compounds such as glucose, which are used to build structural components like cellulose and lignin. Over time, as trees grow, they sequester increasing amounts of carbon in their woody tissues. Mature forests, particularly tropical and temperate forests, are among the largest terrestrial carbon reservoirs due to their high biomass density and long-lived vegetation (Pan *et al.*, 2011a).

The rate of carbon accumulation in woody vegetation depends on several factors, including species composition, climate conditions, soil fertility, and disturbance regimes. Fast-growing species tend to accumulate carbon rapidly during early successional stages, while mature forests store large quantities of carbon but with slower annual accumulation rates. In contrast, degraded forests or areas affected by deforestation and land-use change often exhibit reduced carbon storage capacity and may even become net carbon sources (IPCC, 2021).

Forest ecosystems contribute significantly to the global carbon balance. According to recent estimates, global forests store approximately 861 G/tons of carbon in vegetation and soils combined, with a substantial portion stored in woody biomass (Pan *et al.*, 2011a). Tropical forests alone account for nearly half of the world's forest carbon stock due to their dense vegetation and high productivity (IPCC, 2021). The preservation and restoration of these forests are therefore essential for maintaining and enhancing carbon sequestration.

In addition to natural forests, agroforestry systems and urban green spaces also contribute to carbon build-up in woody vegetation. Agroforestry systems, which integrate trees with crops or livestock, have been recognized as effective strategies for enhancing carbon storage while maintaining agricultural productivity. These systems can store significant amounts of carbon both above and below ground, depending on tree density and management practices (Jose, 2009). Similarly, urban trees contribute to carbon sequestration and provide additional ecosystem services such as cooling, air purification, and biodiversity support.

Disturbances such as deforestation, forest fires, pests, and disease outbreaks can significantly reduce carbon stocks in woody vegetation. When trees are cut or burned, the carbon stored in their biomass is released back into the atmosphere as CO_2, contributing to greenhouse gas emissions (Friedlingstein *et al.*, 2022). This process underscores the importance of sustainable forest management practices that minimize carbon losses and promote regeneration and reforestation.

Soil also plays a crucial role in the carbon dynamics of woody vegetation systems. A portion of the carbon fixed by trees is transferred to the soil through litter fall, root turnover, and decomposition. Soil organic carbon can persist for long periods, making it an important long-term carbon reservoir. The interaction between vegetation and soil carbon pools is vital for understanding ecosystem-level carbon storage and cycling (Lal, 2004).

Climate change influences the build-up of carbon in woody vegetation in complex ways. Elevated CO_2 concentrations can stimulate plant growth and enhance carbon sequestration (a phenomenon known as CO_2 fertilization) . However, this effect may be limited by nutrient availability, water stress, and increasing temperatures. Additionally, climate-induced disturbances such as droughts, storms, and wildfires can offset gains in carbon storage by increasing tree mortality and reducing forest cover (IPCC, 2021).

Human activities have both positive and negative impacts on carbon build-up in woody vegetation. Reforestation, afforestation, and forest conservation efforts enhance carbon sequestration, while deforestation, land conversion, and unsustainable logging reduce carbon stocks (Jose, 2009). International initiatives such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) aim to incentivize developing countries to reduce forest loss and promote carbon storage in forests, thereby contributing to global climate mitigation goals (IPCC, 2021).

In conclusion, the build-up of carbon in woody vegetation is a vital ecological process with significant implications for climate regulation, biodiversity conservation, and ecosystem sustainability. Protecting existing forests, restoring degraded lands, and promoting sustainable land-use practices are essential strategies for enhancing carbon sequestration in woody vegetation. As the global community seeks solutions to climate change, woody vegetation will remain a key natural ally in capturing and storing atmospheric carbon.

2.6.3 Aboveground Biomass Carbon Stock

Carbon sequestration can be defined as the removal of CO2 from the atmosphere and store into green plant biomass (sink) where it can be stored indefinitely through the process of photosynthesis(FAO, 2005). These sinks can be above ground biomass (trees), living biomass below the ground in the soil (roots and microorganisms) or in the deeper sub-surface environments (Ramachandran Nair *et al.*, 2009). Forests are major contributors to terrestrial carbon sink, mitigating climate change and associated economic benefits (Watson *et al.*, 2000; FAO, 2005; Sheikh *et al.*, 2009). As a leading tree based system, especially in the tropics, agroforestry, afforestation and reforestation has been suggested as one of the most appropriate land management systems for mitigating the atmospheric carbon increase (IPCC, 2000a; Montagnini *et al.*, 2004). The estimation of the total global carbon sequestration potential for afforestation and reforestation activities for the period 1995-2050 was between 1.1-1.6 Gt carbon per year and of which 70% will be in the tropics (IPCC, 2000a). Even though the climate protection role of forests is apparent, it is complex to determine how much of the forest carbon sink and reservoir can be managed to mitigate atmospheric CO2 and in what way to build-up. Four major strategies are available to mitigate carbon emissions through forestry activities: (i) increase forest land area through reforestation and afforestation, (ii) increase the carbon density of existing forests at both stand and landscape scales, (iii) expand the use of forest products that sustainably replace fossil-fuel, and (iv) reduce emissions from deforestation and degradation (Ramachandran *et al.*, 2007; Canadell *et al.*, 2008).

Deforestation and the burning of forests release CO2 to the atmosphere. Indeed, land use and land cover change especially deforestation is responsible for about 25% of all greenhouse emissions to the atmosphere (Watson *et al.*, 2000). On the other hand, forest ecosystems could also help reduce greenhouse gas concentrations by absorbing carbon from the atmosphere through the process called photosynthesis. Of all the global forests, tropical forests have the greatest potential to sequester carbon primarily through reforestation, agroforestry and conservation of existing forests (Brown, 2002).

2.6.4 Below Ground Biomass Carbon Stock

Roots are an important part of the carbon balance, because they transfer large amounts of carbon into the soil (Jackson *et al.*, 2017). A substantial proportion of the carbon assimilated by plants is transported below-ground through root growth and turnover, root exudates, and litter deposition (Abramoff, 2015). Depending on rooting depth, a considerable amount of carbon is stored below the plow layer and better protected from disturbances, which leads to longer residence times in the soil (Paustian *et al.*, 2016). With some trees having deep rooting systems, root carbon inputs can be substantial, although the amount generally declines with soil depth (Canadell *et al.*, 2021). Root biomass in ecosystems is often estimated using root-to-shoot ratios, which vary across ecosystems, with lower ratios in tropical forests and higher ratios in temperate and boreal forests (Ritter *et al.*, 2026).

Roots make a significant contribution to soil organic carbon (SOC) (Friedlingstein *et al.*, 2022). A large portion of the carbon fixed in photosynthesis is transported belowground and partitioned among root growth, rhizosphere respiration, and incorporation into soil organic matter (Li *et al.*, 2023). Roots help in the accumulation of SOC through decomposition and by supplying carbon to the soil via rhizodeposition (Jackson *et al.*, 2017). Increased production and turnover rates of roots can enhance SOC accumulation following root decomposition (Silver *et al.*, 2001).

2.6.5 Dead Wood Biomass Carbon Stock

Dead organic matter is composed of litter and dead-wood and generally divided into course and fine, with the breakpoint set at 10 cm diameter (Takahashi *et al.*, 2010). Although logged dead wood, standing and lie down on the ground, is often a significant component of forest ecosystems, often accounting for 10-20% of the aboveground biomass in mature forests but it tends to be ignored in many forest carbon budgets(Delaney *et al.*, 1998). The quantity of dead wood does not generally correlate with any index of stand structure (Harmon *et al.*, 1996). The primary method for assessing carbon stock in the dead wood pool is to sample and assess the wet-to-dry weight ratio, with the large pieces of dead wood measured volumetrically as cylinders and converted to biomass on the basis of wood density, and standing trees measured as live trees but adjusted for losses in branches (<20%) and leaves (<2-3%) (MacDicken, 1997).

Dead trees serve many key functions in the ecosystems (Franklin *et al.*, 1987). Since dead trees may persist for centuries, they can influence ecosystems as long as living trees. Woody detritus reduces erosion, they are a major source of energy and nutrients, serves as a seedbed for plants and they are a major habitat for microbes, invertebrates and vertebrates(Harmon *et al.*, 1996).

2.6.6 Litter Carbon Stock

Carbon is stored in trees (stem, branches, leaves and root), understory, and forest litter and forest soils. The mechanism of species driven carbon sequestration in soil is influenced by two major activities, aboveground litter decomposition and belowground root activity (Lemma *et al.*, 2007). Litter decomposition is one of the major sources of SOC and the quality of litter is very important in this regard (Lemma *et al.*, 2007). In the systems with high plant diversity, litters are present with different degrees of chemical resistance, creating the possibility of longer residence of carbon through slower decomposition of litters from some species. Lignin in litter is highly resistant to decomposition and therefore, litter with high lignin content would have slower decomposition rate (Mafongoya *et al.*, 1998). In contrast, litter with low lignin, phenols, and high nitrogen content would have faster rate of decomposition.

2.7 Church forest for carbon sequestration in mitigating climate change

Climate change mitigation can be achieved by limiting (Preventing) greenhouse gas emissions and by enhancing the activities that can remove these gases from the atmosphere. Limiting the global warming below or close to 1.5 °C from pre-industrial levels would require to decrease net emissions of greenhouse gas by around 45% by 2030 (UNFCCC, 2015a). It is required to remove from 100-1000 Gt CO2 over the 21st century to achieve the limit of global warming to 1.5°C (UNFCCC, 2015a).

One option for slowing down the rise of greenhouse gas concentrations in the atmosphere, and thus possible climate change, is to increase the amount of carbon removed and stored in forests (UNFCCC, 2015a). When trees grow, they sequester carbon in their tissues, and as the amount of tree biomass increases within a forest the increase in atmospheric CO2 is mitigated. The ability of these plantations to sequester carbon has received renewed interest since carbon sequestration projects in developing nations could receive investments from companies and governments wishing to offset their emissions of greenhouse gases through the Kyoto Protocol's Clean Development Mechanism (Fearnside, 1999). Carbon Sequestration is the process of capturing carbon dioxide and storing it to reduce the accumulation of greenhouse gases in the atmosphere(UNFCCC, 2015a). Church forests can sink carbon so as to mitigate the greenhouse gas emissions that drive climate change (UNFCCC, 2015a).

Forests play a significant role in climate change mitigation by sequestering and storing more carbon from the atmosphere than any other terrestrial ecosystem. EOTC Church forests, including other sacred places, are relatively more protected than forests in any other places (Tura *et al.*, 2017).

2.8 Church forests as in situ biodiversity conservation

The churches and monasteries of the EOTC are often surrounded by natural forest characterized by a high floral and faunal diversity with many indigenous and rare species (Wassie *et al.*, 2006a; Canadell *et al.*, 2008). There are two kinds of church forests in Ethiopia of which the churches older than five hundred years are surrounded by primary forests while recently established churches of the last decades are observed with secondary forests and in this case the older church forests are characterized by a high floral and faunal diversity with many indigenous and rare species. These closely located forests have high ecological importance to form corridors and are important for species exchange and the distribution of genetic resources in conservation (FAO, 2020).

Church forests are the ideal sites to be chosen for species afforestation programs in their specific localities and that could serve as models of biodiversity conservation. Many endangered species of flora in Northern Ethiopia, are found surrounding churches and Monasteries (Tilahun *et al.*, 2015a). The EOTC is making a sustained effort to teach and advise the clergy and the people living in the community; highlight the need to protect existing trees; induce the desire to plant and look after newly planted trees, and in particular care of indigenous trees and plants (Wassie *et al.*, 2006a).

The church forests are the sanctuary of many indigenous species protected in different agro-ecological/climatic zones, could be used as germplasm for regeneration and then to conserve biodiversity (Tilahun *et al.*, 2015a). EOTC church forests are often safe places for trees and other biodiversity resources. In other words, church compounds are serving as in situ conservation and hot spot sites for biodiversity resources, including many endemic and endangered species (FAO, 2020).

2.9 Ethiopian Orthodox Tewahido Church and Climate Change Perception

Many researchers finding stated that effectual climate change adaptation measures and mitigation strategies are found within the local communities while climate perception and attitude plays significant role in climate change risk reduction and avoidance with degree of available adaptation tools vary from one community to another (Dereje *et al.*, 2022).

In a similar way Ethiopian Orthodox Tewahido church plays significant role on building public perception and attitude causes and consequences of climate change and implementation of climate change adaptation strategy in addition to direct carbon sequestration through forests in monastery and church compounds (Tilahun *et al.*, 2015a). The main social purpose of Ethiopian Orthodox Tewahido churches and monasteries are places for worship, burials and meditating religious feasts and festivals in addition to tenable habitats for plants and animals, as well as living organism (FAO, 2020). This provide gold opportunity for the church to guiding, teaching and preaching her followers regarding goods, terrible and coming global concerns including causes and consequences of climate change, appropriate mitigation and adaptation measures.

Most wood species in monastery and church compounds are endemic to afro-mountain vegetation type which is centre for plant genetic diversity and opportunity for climate change mitigation (Feyissa *et al.*, 2013). The unique characteristics of afro-mountain forest ecosystem are its diversity and richness in endemic species (Getaneh *et al.*, 2015). Getachew *et al.* (2012) study stated that, carbon sequestration potential of church forest is comparable with other national and tropical natural forest.

2.10 Ecosystem Services Theory

The Ecosystem Services Theory provides a useful framework for understanding the benefits that humans obtain from ecosystems and how these benefits contribute to human well-being (MillenniumEcosystemAssessment, 2003). The theory classifies ecosystem services into four major categories: provisioning services (e.g., food, fuel wood, and water), regulating services (e.g., climate regulation, carbon sequestration, and erosion control), supporting services (e.g., nutrient cycling and soil formation), and cultural services (e.g., spiritual, religious, and recreational values) (Costanza *et al.*, 1997; MillenniumEcosystemAssessment, 2003).

This theory was selected because the central focus of the study is to examine the role of church forest ecosystems in mitigating climate variability while simultaneously supporting local communities. Church forests provide multiple ecosystem services that directly align with the objectives of the study. Ecologically, they regulate local climatic conditions, store carbon, conserve biodiversity, reduce soil erosion, and enhance ecosystem resilience. Socially and culturally, they provide sacred spaces that support religious practices, cultural identity, and community cohesion. Consequently, Ecosystem Services Theory offers a comprehensive framework for evaluating the ecological and societal benefits generated by church forests.

The theory is particularly relevant to the climate mitigation component of this study because carbon sequestration and climate regulation are recognized as key regulating ecosystem services. By quantifying aboveground and belowground carbon stocks, the study assesses the contribution of church forests to climate change mitigation. Similarly, woody species diversity, forest structure, and regeneration status are indicators of ecosystem functioning that support the continued provision of ecosystem services. Community perceptions of climate variability and forest conservation are also linked to how local people recognize, value, and benefit from ecosystem services provided by church forests.

The application of Ecosystem Services Theory in this study therefore enables the investigation of how church forests contribute to ecological sustainability, climate mitigation, and human well-being across different agroecological zones. It provides the theoretical basis for understanding the relationship between ecosystem functions, ecosystem services, and societal benefits.

However, while Ecosystem Services Theory effectively explains the benefits generated by ecosystems, it provides limited insight into the dynamic interactions between people and ecosystems under conditions of climate variability. To address this limitation, the study is further informed by the Social-Ecological Systems Theory.

Social-Ecological Systems (SES) Theory

The Social-Ecological Systems (SES) Theory, developed by (Ostrom, 2009), conceptualizes humans and ecosystems as interconnected and interdependent systems. The theory argues that environmental outcomes cannot be understood solely through ecological processes or human actions in isolation because both systems continuously interact and influence one another.

According to the SES framework, ecological resources, governance systems, resource users, and external environmental factors collectively determine ecosystem conditions and societal outcomes (Ostrom, 2009). Climate variability acts as an external driver that influences both ecological systems and human communities. At the same time, community perceptions, management practices, and conservation behaviours affect ecosystem resilience and the capacity of forests to provide ecosystem services.

The SES theory is particularly relevant to this dissertation because the study simultaneously investigates climate variability, community perceptions, and church forest ecosystems. Church forests represent a classic social-ecological system in which ecological resources are protected and managed through cultural, religious, and community institutions. Climate variability influences forest structure, regeneration, biodiversity, and carbon sequestration capacity, while local communities observe these changes, develop perceptions about them, and respond through adaptation and conservation practices.

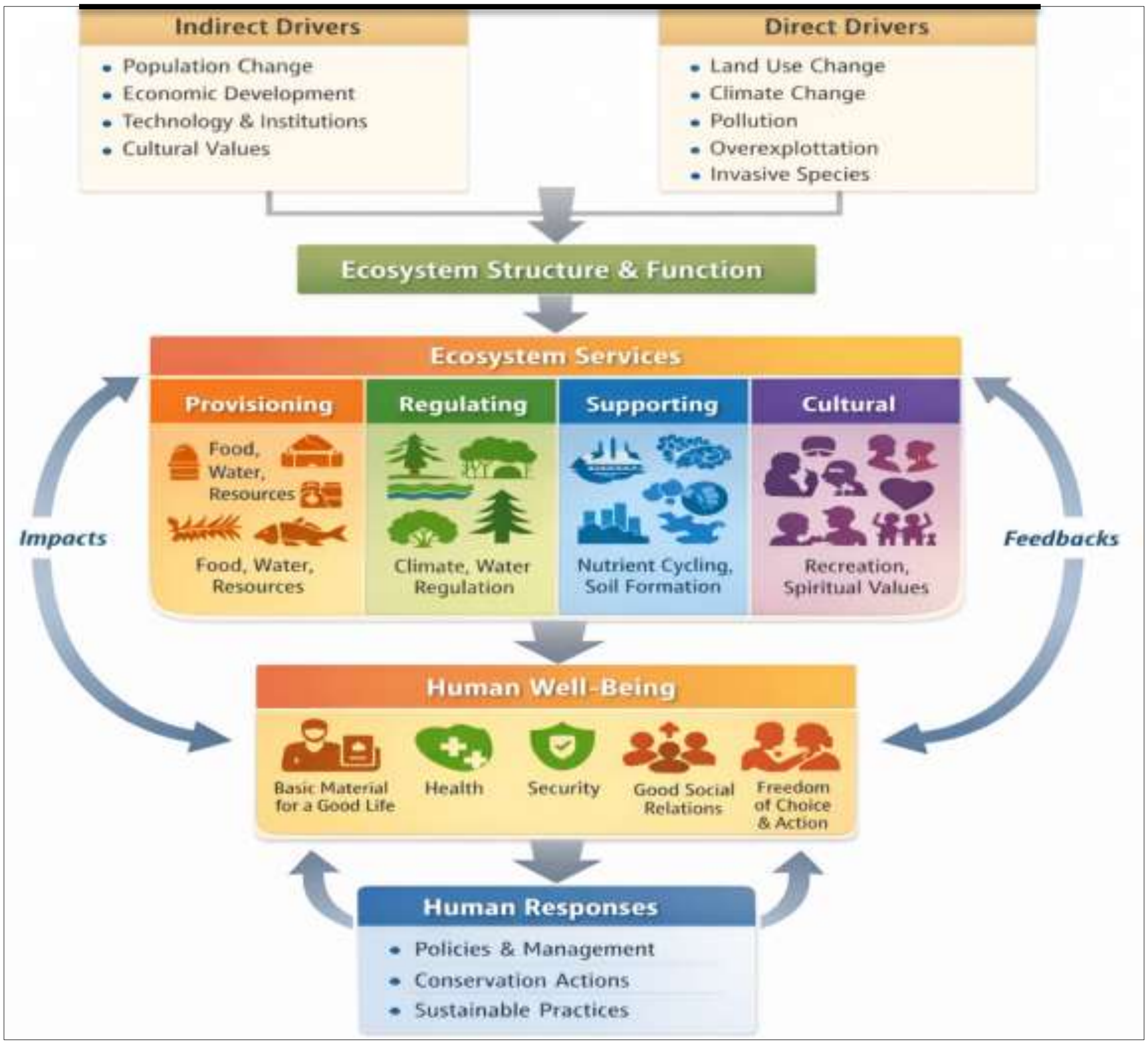
The theory also provides a strong foundation for examining agroecological variability. Different agroecological zones exhibit variations in temperature, rainfall, soil conditions, vegetation characteristics, and livelihood systems. These differences influence both ecosystem responses to climate variability and community perceptions of climatic change. Consequently, the SES framework helps explain how environmental conditions and social factors interact differently across agroecological zones to produce varying ecological and social outcomes.

Integration of Ecosystem Services Theory and SES Theory

The integration of Ecosystem Services Theory and Social-Ecological Systems Theory provides a comprehensive theoretical foundation for this study. Ecosystem Services Theory explains what benefits church forests provide, particularly their climate regulation and carbon sequestration functions. Social-Ecological Systems Theory explains how climate variability, local communities, and church forest ecosystems interact to influence the provision and sustainability of these ecosystem services.

In this study, climate variability serves as an external environmental driver affecting both ecological systems and human communities. Church forests constitute the ecological subsystem that generates ecosystem services such as biodiversity conservation, carbon sequestration, and climate regulation. Local communities represent the social subsystem whose perceptions, beliefs, and management practices influence forest conservation and ecosystem resilience. Agroecological conditions shape the interactions between these ecological and social components. Together, these theories enable an integrated assessment of climate variability, community perceptions, and the mitigation role of church forest ecosystems across agroecological zones.

Therefore, the combined application of Ecosystem Services Theory and Social-Ecological Systems Theory provides a robust framework for understanding not only the climate mitigation benefits of church forests but also the complex interactions among climate, ecosystems, and human societies that determine the sustainability of these benefits.

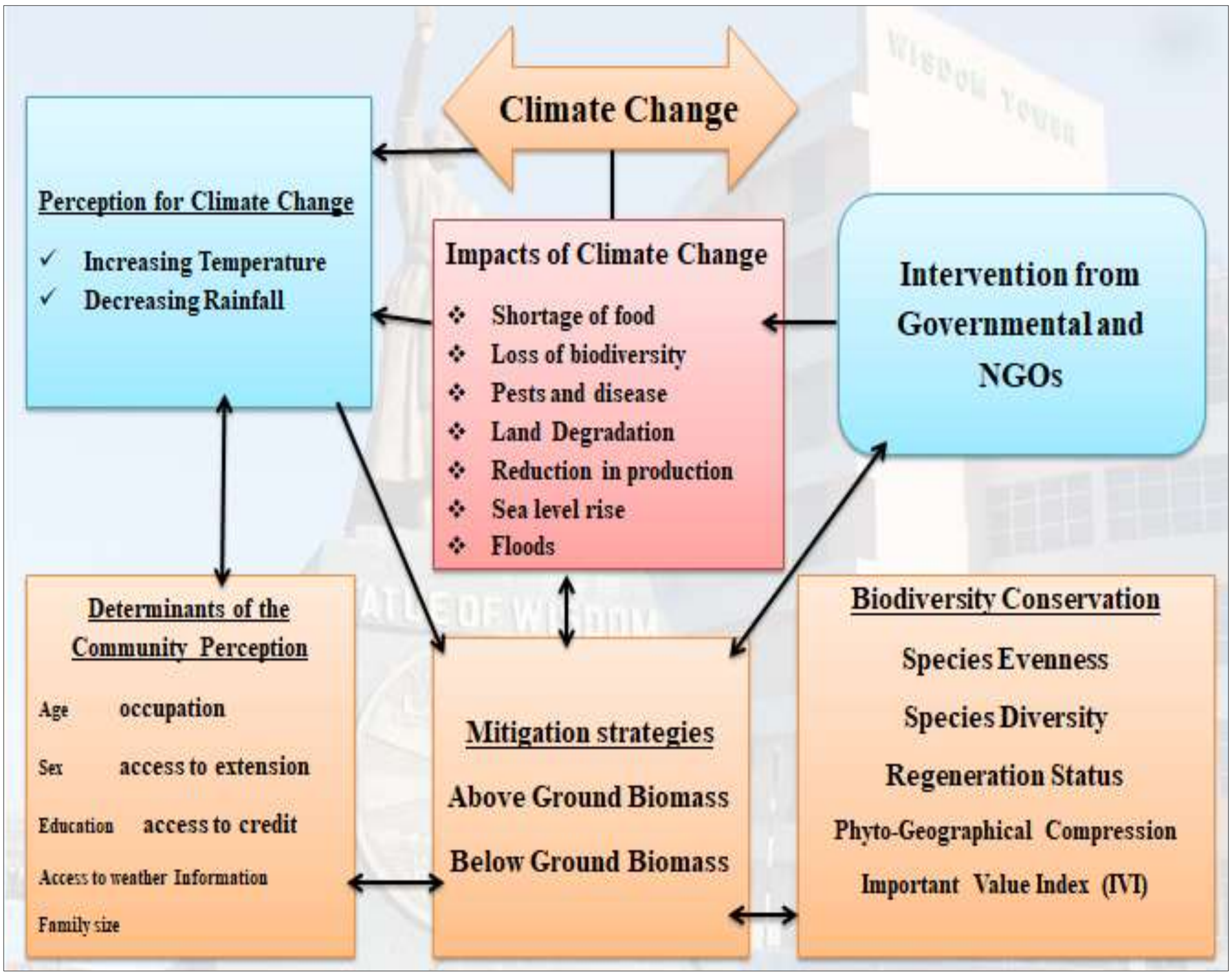


2. 1 Theoretical framework

Source: Adopted from Millennium Ecosystem Assessment (2005)

2.11 Conceptual Framework of the Study

The changes in climatic conditions were manifested by an increase in temperature and decrease in rainfall availability so that emergence of unfavourable situation for the whole human wellbeing. Climate change thus causes adverse impacts on livelihood of farmers. Farmers then have to perceive climate change and its adverse impacts on their agricultural production and their livelihood in order to respond to the change so that capable to lessen side effects. There is also an awareness creation and some other intervention from government and non-government organizations to enable farmers to perceive climate change and to take mitigation measures. Farmers then took certain measures to adapt to climate change based on their perception and intervention from governmental and non-governmental organizations. In fact, there are a number of mitigation options from which farmers made a choice. Farmer's mitigation of particular measures was subject to various household and institutional factors. The following analytical framework depicted the most important variables expected to influence the farmer's choice of mitigation strategies to climate change the case of Jabitehinan District (Figure 2.2).



2. 2 Conceptual Frameworks

Source: - Own synthesis based on literature reviews

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Description of the Study Area

Location

Jabitehnan Woreda is found in the Amhara National regional state, at West Gojjam zone of Ethiopia. It is located on 10^0 30' 0" N-10^0 50' 0" N 37^0 4' 0" E-37^0 32' 0" E (Figure 3.1). The majority of the woreda lies in altitude from 1500-2300m. The topography is characterized by plains (65%), mountainous terrain (15%), valleys (15%), and other landforms (5%) *(Teshome et al., 2022)*. The temperature of the woreda ranges between 14_c^o to 32_c^0, with an annual average of 23_c^0. The average annual rainfall is 1250mm per annum (Getachew *et al.*, 2023). Small-scale mixed farming is the main economic activity in the rural community of the district, with crop production being the major economic activity followed by livestock production. The district is known as area of surplus production of all kind of farming production of all cereal and cash crop production. Livestock production is the second most important economic activity for the district a whole (Tola *et al.*, 2025). Jabitehinan district is selected as the study area for the following reasons. Based on the availability of agro-ecological zones and the intensity of the impact of the climate change and variability, there are historical monasteries found with the indigenous forest coverage, as a result to give especial attention. Lastly there are no any studies regarding with this topic before now.

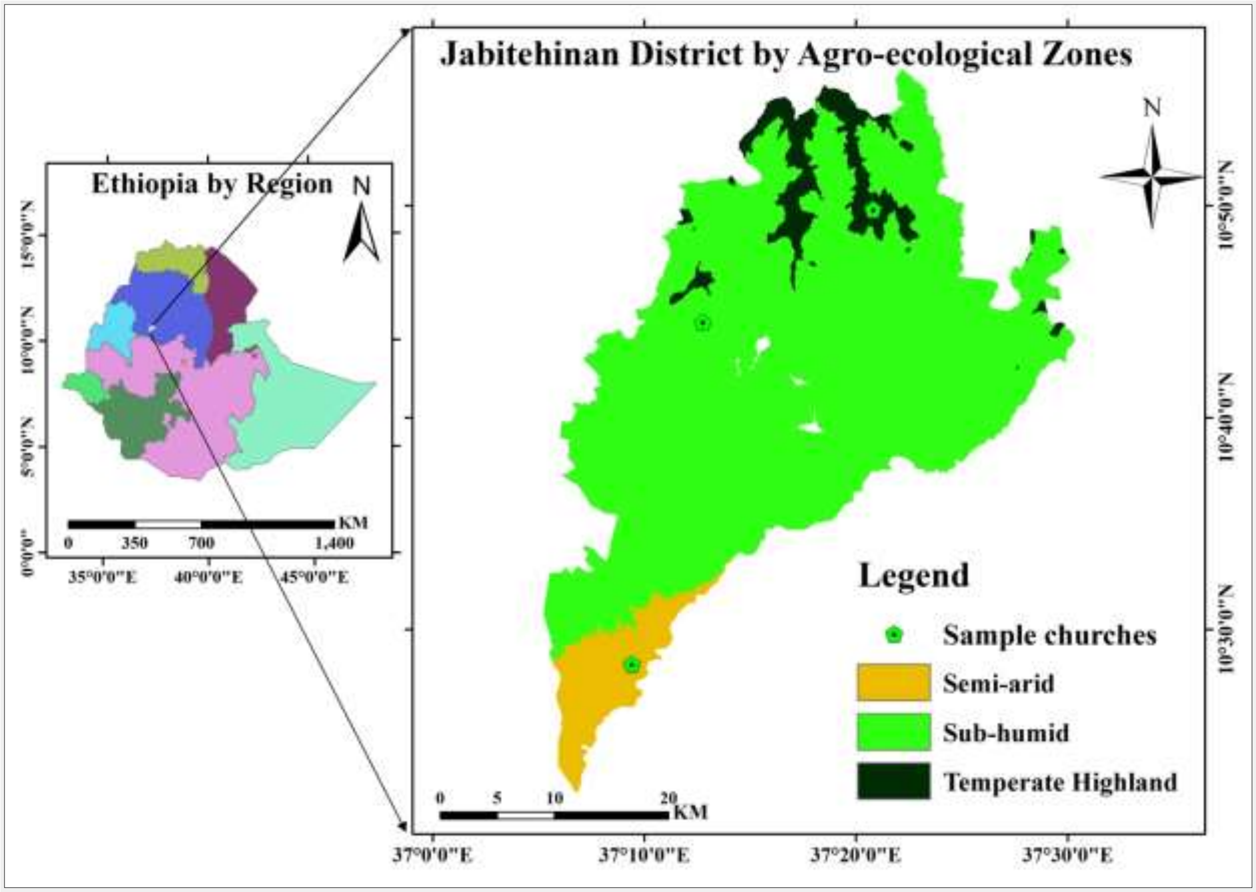


Figure3. 1 Study area Map

Elevation and Slope of the study area

The map (Figure 3.2) vividly illustrates Africa's greatest highland massif rising prominently from Ethiopia's extensive lowland areas. The landscape of Jabitehinan District is characterized by pronounced topographic variability, marked by a highly diversified and dissected terrain. Rugged landforms, deeply incised surfaces, and very steep slopes constitute the distinctive physical features of the district (MinistryofWater, 2016).

The altitudinal range of the area extends from semi-dry plains located at approximately 1,186 meters above sea level around Jamo in the southern part of the district, to high mountainous peaks reaching about 2,830 meters above sea level at Mount Ambisgama in the northern section (MinistryofWater, 2016). This substantial elevation gradient reflects the complex geomorphological evolution of the Ethiopian Highlands.

The elevation profile (Figure 3.2) further indicates that the northern and northwestern parts of the central landscape attain very high altitudes, exceeding 2,830 meters above sea level. In contrast, the southern, western, and southwestern peripheral escarpments are dominated by much lower elevations, falling below 1,186 meters above sea level over relatively short horizontal distances. This sharp altitudinal contrast highlights the steep escarpments and highly dissected nature of the district's terrain (MinistryofWater, 2016).

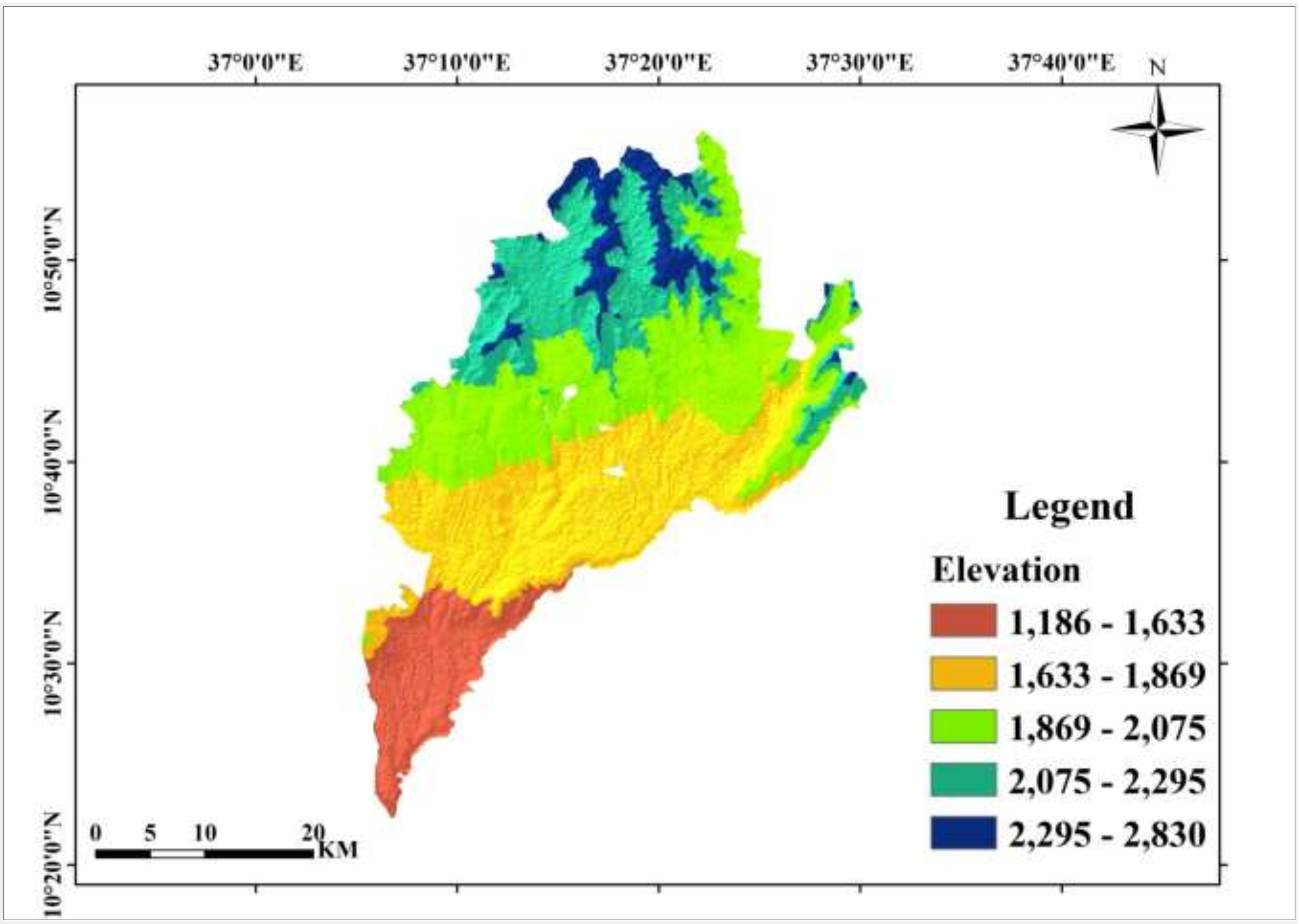


Figure3. 2 Elevation map of the study area (NASAandMETI, 2022)

Slope is a fundamental component of the land surface and plays a crucial role in controlling drainage patterns, surface runoff, and soil erosion processes. According to the FAO (2020) slope classification system, soil depth generally decreases with increasing slope gradient, thereby influencing land capability and susceptibility to degradation. Based on the FAO classification, the slope of the study area was categorized into five classes: 0–2.2%, 2.2–5%, 5–9.3%, 9.3–15.5%, and 15.5–35.6% (Figure 3.3). These slope classes correspond to flat to nearly level terrain (0–2.2%), gently sloping land (2.2–5%), sloping terrain (5–9.3%), strongly sloping areas (9.3–15.5%), and steep to very steep slopes (15.5–35.6%). The analysis indicates that approximately 30% of the study area is characterized by slopes greater than 9.3%, suggesting a considerable proportion of land with high erosion risk and limited suitability for intensive agricultural use.

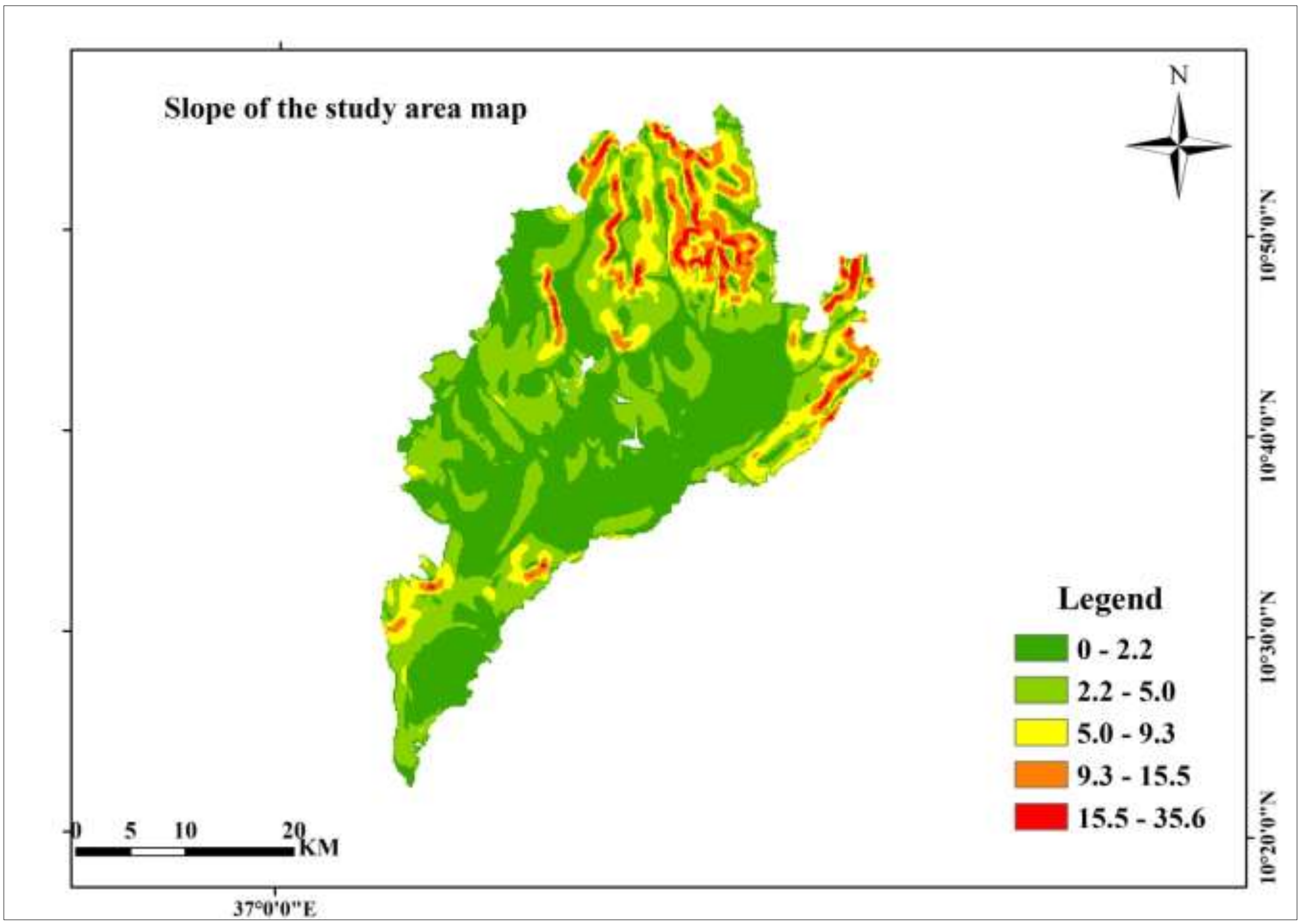


Figure3. 3 Slope map of the study area (NASAandMETI, 2022)

Soil types of the study area

Soil is a fundamental component of the land surface, and its characteristics vary based on texture, structure, organic matter content, and permeability. In the study area, the major soil types include Chromic Luvisols, Chromic Vertisols, Dystric Nitosols, Eutric Nitisols, Eutric Vertisols, and Leptosols. Among these, Chromic Vertisols (1835.9 km^2), Eutric Nitisols (1489.2 km^2), and Chromic Luvisols (1176.8 km^2) are dominant, collectively covering about 91.6% (4501.9 km^2) (Figure3. 4 **)** of the district (MoA, 2020).

In terms of agricultural importance, Eutric Nitisols and Chromic Vertisols are highly productive due to their fertility and suitability for major crops such as cereals and pulses, although Vertisols face drainage challenges. Chromic Luvisols are moderately fertile and suitable for a wide range of crops but require proper soil management. Dystric Nitosols are less fertile and need soil amendments, while Eutric Vertisols are fertile but constrained by poor workability. In contrast, Leptosols have limited agricultural value due to their shallow depth and are mainly used for grazing and conservation.

The district is dominated by agriculturally important soils, though their productivity depends on appropriate management practices such as drainage improvement, soil fertility enhancement, and conservation measures.

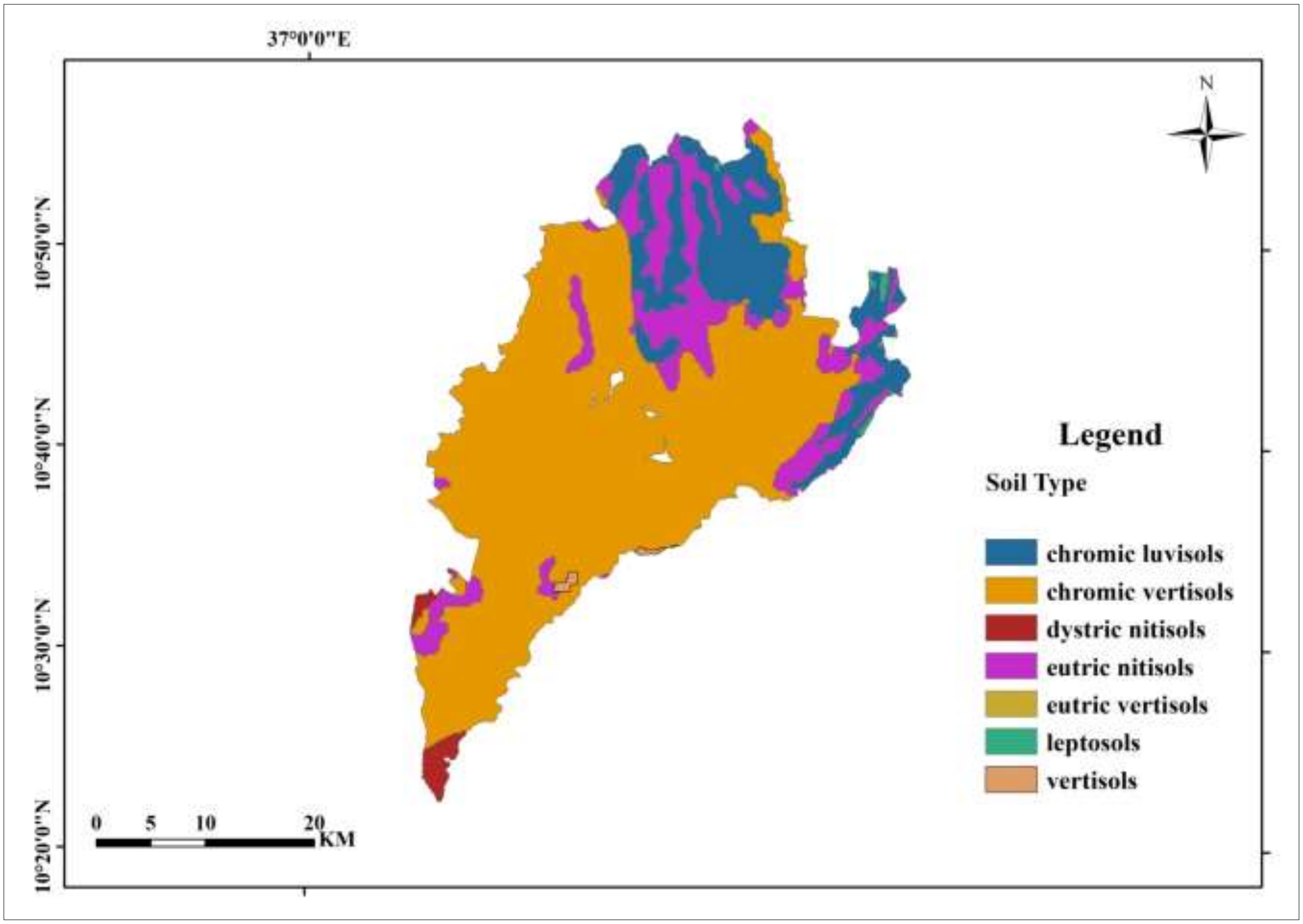


Figure 3. 4 Soil type of the study area (FAO, 2012)

Economic Activities: Livelihood based activities

The district is characterized by a distinctive bi-modal rainfall regime locally known as summer (big rainy season) and autumn and spring *(*small rainy season). Summer season usually extends from June-to-September while the autumn and spring season usually extends from February-to-May(USAID, 2009). Seasonal patterns of crop production (planting and harvesting) activities are very multifaceted. On the other hand, autumn and spring livelihood district's crop production follows the bimodal rainfall regimes (small autumn and spring and big Summer rainy seasons) leading to two harvest periods, but the autumn and spring harvest season is by far the most important for livelihood and summer is the most important for the cultivation of both long and short cycle crops of autumn and spring livelihood zone (USAID, 2009). The old-style subsistence farming (a mix of both grain production and rearing of livestock) was the primary form of economic activities in all livelihood zones of the study area. The existence of diverse agro ecology enables the zone to raise different types of livestock and to produce different types of cash and cereal food crops (ANRSPC, 2017). The most dominant cereal crops produced include teff (*Eragrostis tef*), sorghum (*Sorghum bicolor*), maize (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and pulses (*Leguminosae/Fabaceae*). The cultivation of staple is complemented by a variety of cash crops that include chat, tobacco, fruits, and vegetables (USAID, 2009).

The agricultural activities are entirely rain-fed except in some pocket areas where small-scale irrigation and water harvesting practices in a small number of localities. Even though either the small or large-scale irrigation practices were very minimal, the district is known by a number of large and small rivers that categorized into two major drainage basins: Abay and Choke watershed accounting about 82% and 18% of the area respectively (ANRSPC, 2017). Nevertheless, the larger reliance on agriculture-based income, which is under the sensitivity of nature (unreliable and erratic rainfall), exposed the people to climate variability (Ademe *et al.*, 2020). Besides, the practice of agriculture challenged by small per capita land possession as well as mis-use and mis-management of land resulted in high soil erosion and low soil fertility and conversion of grazing and forest lands to agricultural area (ANRSPC, 2017). All these attributes contributed to the reduction of productivity in the district.

Livestock production in the study region is subsistence oriented. Its livestock production is well integrated with crop production. The farming system is dependent on livestock for food, security and survival. The area under study is endowed with diverse livestock population. Cattle, goats, sheep and equines are the major livestock, which are all kept in widely different types of environment from the cool highlands (>2,830 meter above sea level) to the hot pastoral rangelands (MoA, 1998). Substantial parts of the cropping area of the district, millions of people today get more cash from crop than livestock. However, the contribution of livestock in the livelihood of people highly questioned by the main internal and external livestock diseases and parasites, including Anthrax, black leg, sheep and goat pox, African horse sickness, pasteurellosis, prevalent in the area (USAID, 2009).

3.2 The research philosophy, Approach, and design

Pragmatism is adopted as the guiding research philosophy in this study because it emphasizes practical solutions to real-world problems and prioritizes the research question over strict adherence to a single epistemological stance (Morgan, 2014). Rooted in the idea of "what works," pragmatism allows researchers to draw on both objective and subjective knowledge to better understand complex phenomena (Tashakkori *et al.*, 2021). This philosophy rejects the dichotomy between positivism and interpretivism and instead promotes methodological pluralism, where different approaches are combined to generate meaningful and actionable knowledge. As noted by (Creswell *et al.*, 2007), pragmatism provides a flexible philosophical foundation that supports the integration of multiple methods to address multifaceted research problems.

The adoption of pragmatism in this study is strongly justified by the complex and interdisciplinary nature of climate change research, which involves environmental, social, and economic dimensions (Coyle *et al.*, 2018). Understanding climate variability, ecological responses, and farmers' perceptions requires the use of diverse data sources and analytical techniques. A purely quantitative or qualitative approach would be insufficient to capture the full scope of the problem. Pragmatism, therefore, enables the researcher to combine quantitative data (such as climate records, GIS analysis, and carbon estimation) with qualitative insights (such as local knowledge and their perception) (Coyle *et al.*, 2018). This approach enhances the depth and validity of the findings by providing a more comprehensive understanding of the research problem (Tashakkori *et al.*, 2021).

In practice, the pragmatist philosophy is reflected in the methodological choices of this study through the adoption of a mixed-methods research design. Quantitative techniques are employed to analyze climate data trends, spatial patterns, and carbon sequestration potential, while qualitative methods such as household surveys and key informant interviews are used to explore farmers' perceptions. The integration of these methods allows for triangulation and strengthens the reliability of the results. This methodological flexibility demonstrates the pragmatic principle that research methods should be selected based on their ability to effectively address the research objectives and produce useful outcomes (Chih-Pei *et al.*, 2017). Accordingly, the study aligns with the pragmatist view that knowledge is best developed through the combination of approaches that provide practical and context-relevant solutions (Morgan, 2014).

A mixed research approach was employed in this study, specifically adopting a concurrent embedded design, in which both qualitative and quantitative data were collected and analyzed within a single phase of the research process. Mixed methods research enables the integration of numerical and textual data to provide a more comprehensive understanding of complex research problem (Tashakkori *et al.*, 2021). It allows the researcher to collect and analyze both forms of data and to integrate them at different stages, thereby enhancing the depth and validity of findings. As noted by Creswell *et al.* (2007), mixed methods facilitate a more complete interpretation of research problems by combining the strengths of both approaches. More recent studies also emphasize that mixed methods research is particularly valuable in addressing multifaceted environmental and social issues, where a single approach may be insufficient (Coyle *et al.*, 2018).

The use of a mixed research approach in this study is justified by its ability to overcome the limitations associated with relying solely on either quantitative or qualitative methods. Quantitative approaches are effective in measuring and analyzing trends, patterns, and relationships, while qualitative approaches provide deeper insights into perceptions, experiences, and contextual realities. By combining these approaches, the study benefits from methodological complementarity, enabling a more holistic understanding of climate change impacts. Furthermore, mixed methods offer flexibility through various design options, including sequential and concurrent strategies, allowing researchers to examine problems from multiple perspectives (Creswell *et al.*, 2007; Chih-Pei *et al.*, 2017; Coyle *et al.*, 2018). This integrative approach is particularly important for studies that aim to address complex environmental challenges and human responses simultaneously.

In practice, the concurrent embedded mixed-methods design was applied by prioritizing quantitative data while embedding qualitative data to complement and enrich the analysis. Quantitative data, including climate variables such as rainfall and temperature, as well as carbon sequestration and biodiversity indicators, were analyzed using statistical and spatial techniques to assess trends and patterns in the study area. At the same time, qualitative data were collected through household surveys and interviews to explore farmers' perceptions of climate change. The integration of these datasets allowed for triangulation and improved the reliability of the findings. This approach aligns with contemporary mixed-methods practice, which emphasizes the importance of integrating diverse data sources to generate comprehensive and context-relevant insights (Creswell *et al.*, 2007; Chih-Pei *et al.*, 2017; Coyle *et al.*, 2018).

A concurrent embedded research design is a type of mixed-methods design in which both quantitative and qualitative data are collected during the same phase of the study, but one method is given priority while the other is embedded to provide additional insight (Creswell *et al.*, 2017). In most cases, the dominant approach (often quantitative in environmental studies) addresses the main research questions, while the secondary method (qualitative) plays a supportive role by helping to explain or enrich the primary findings. According to (Morgan, 2014), the embedded design is particularly useful when a researcher needs to collect different types of data simultaneously but still maintain a clear priority on one form of data. This design is commonly used when a study involves complex phenomena that require both measurement (quantitative) and contextual understanding (qualitative).

The selection of a concurrent embedded design in this study is justified by the nature of the research problem, which involves both biophysical measurements and human perceptions. Climate variables such as rainfall and temperature, along with carbon sequestration and biodiversity assessments, require quantitative analysis to identify patterns and trends. At the same time, understanding farmers' perceptions and responses to climate change requires qualitative exploration. A fully quantitative design would not capture social and behavioural dimensions, while a purely qualitative design would lack the ability to measure environmental changes. Therefore, the embedded design was selected because it allows the integration of qualitative insights into a predominantly quantitative framework, providing a more comprehensive understanding of the research problem. As noted by Tashakkori *et al.* (2021) and Chih-Pei *et al.* (2017), embedded designs are particularly appropriate when one data type is used to support or enhance the primary method, especially in complex, real-world studies.

In this study, the concurrent embedded design directly shaped the methodological choices by guiding the simultaneous collection of both quantitative and qualitative data. The quantitative component formed the core of the study, where climate data (rainfall and temperature), carbon sequestration, and biodiversity indicators were analyzed using statistical and spatial techniques. These data provided objective measurements of environmental changes in the study area. The qualitative component, embedded within the design, involved household surveys and key informant interviews to capture farmers' perceptions of climate variability. The integration of these components occurred during interpretation, where qualitative findings were used to explain and contextualize the quantitative results. This approach reflects the embedded design's emphasis on complementarity and triangulation, enhancing the credibility and depth of the findings. As emphasized by Morgan (2014), integrating multiple forms of data in a single study strengthens the overall understanding of complex research problems and supports more robust and actionable conclusions.

3.3 Sampling Technique

The present study employed a mixed sampling strategy, integrating both probability and non-probability techniques to ensure the inclusion of information-rich cases alongside statistically representative respondents. In the qualitative component, purposive sampling was used to select church forests and key informants, while in the quantitative component, stratified random sampling and systematic sampling were applied to select household respondents. Combining these techniques is widely recommended in mixed-methods research to enhance both depth and generalizability of findings (Creswell *et al.*, 2023). This approach enabled the study to capture detailed contextual insights while maintaining statistical rigor in household-level data.

Purposive sampling, a type of non-probability sampling, was specifically employed to select church forests and kebeles based on predefined criteria. These criteria included agro-ecological variation (Dega, Woina-Dega, and Kolla) and the observed intensity of climate change impacts. The rationale for choosing purposive sampling lies in its effectiveness in identifying cases that is particularly informative for the research objectives. As noted by Etikan *et al.* (2016), purposive sampling allows researchers to deliberately select units that possess specific characteristics relevant to the study, thereby improving the richness and relevance of the data. In this study, church forests were not uniformly distributed across the district, and their ecological significance varies; hence, purposive selection ensured that representative and ecologically meaningful sites were included. Furthermore, this technique is suitable when time and resources are limited and when the research requires focused investigation of particular phenomena (Palinkas *et al.*, 2015).

For the quantitative component, stratified random sampling was first employed to ensure proportional representation of households across the three agro-ecological zones of Jabitehinan District: Dega (temperate highland), Woina-Dega (sub-tropical), and Kolla (semi-arid). Stratification helped to reduce sampling bias and improve the precision of estimates by grouping relatively homogeneous units before sampling (Lohr, 2021). Following this, a two-stage sampling procedure was implemented. In the first stage, three kebeles Zengebal Bedega, Woga Guanesa, and Ergib Kebromeda were selected purposively based on agro-ecological representation and climate vulnerability. In the second stage, a total of 361 smallholder households were selected proportionally from these kebeles using systematic sampling.

Systematic sampling was applied using household lists obtained from kebele administrators and development agents. After determining the sampling interval (k), a random starting point was selected, and every k^{th} household was included until the required sample size was reached. This method is particularly efficient when a complete sampling frame is available and ensures a spread of samples across the population (Thompson, 2012). By integrating purposive, stratified, and systematic sampling techniques, the study achieved a balanced design that ensured both contextual relevance and statistical representativeness, thereby strengthening the validity and reliability of the research findings (Table 3.2).

Table 3. 1 sample distribution of household respondents across selected kebeles and agro-ecological zones in the Jabitehinan District

No	Name of Kebeles	Agro-climatic Zone	House Hold size	Sample size
1	Zengebal Bedega	Dega (Temperate-Highland)	1160	116
2	Woga Guanesa	Woina Dega (Sub-humid)	1530	153
3	Ergib Kebromeda	Kolla (Semi-arid)	920	92
			3,610	361

Key informants and FGD participant selection was carried out those kebeles a knowledgeable person who has valuable viewpoints about local observed facts and opinions related to climate variability. Six KI interviewees include experts at regional and district level selected purposively based on their work experience and educational status to give detail information about climate variability and the perception of the community. The recruited participants in FGD integrated male and female households, local community leaders. There were four FGD groups; One FGD comprised six participants to discuss on the issue of climate change and variability to answer the second objective the perception of the community.

Aboveground and belowground biomass were estimated using morphometric measurements of standing vegetation, including the stem and canopy characteristics of trees and shrubs across different strata, as well as associated litter and debris. The above mentioned sample district selected by using purposive sampling due to the availability of historical monastery with enough indigenous church forest coverage (Awunet Abo Monastery, Guanesa Medahinalem Monastery, and Zengebal Giorgis church).

The methodology for field data gathering followed the Manual for Building Tree Volume and Biomass Allometric Equations prepared by Food and Agriculture Organization (PicardSaint-André *et al.*, 2012b). Biomass data were collected from 20 sample plots in each selected church forest. The forests were purposively chosen due to their long establishment history and their relatively high abundance of indigenous forest cover (Awunet Abo Monastery, Guanesa Medahinalem Monastery, and Zengebal Bedega Giorgis church). The sampling quadrats of 15 x 15 m (225m^2), 10 x 10 m (100m^2) and 5 x 5 m (25m^2) (Table 3.3 and Figure 3.5), nested within each other, were defined as the units for sampling the landscape and measuring biomass (Kuyah *et al.*, 2012). The distance between the main plots were 50 m along each of the line transects. A total of 10 line transects were laid a single transect from the church building to every 4 directions of each church forests of the study area at 50 m intervals from each other. All tree diameters in the larger plot were measured at breast height (DBH) (1.3 m aboveground level) and at stump height (DSH) (30 cm aboveground level) (PicardSaint-André *et al.*, 2012a). In addition, the total tree heights to the top of the crown were measured using Hypsometer. The dimensions of the quadrats coincide with recommended practice in the ecological literature and represent a compromise between recommended practice, accuracy and practical considerations of time and effort (Jina *et al.*, 2008).

Table 3. 2 Use of each nested quadrat site for sampling and measurement

Quadrats	Use Of Quadrat In Measurements And Sampling
15×15	Morphometric measurements of the tree layer. Measurements of trunk and canopy of trees and large deadwood. Identification of tree species and individual organisms within a species for biodiversity assessment.
10×10	Study of the shrub layer. Morphometric measurements of the shrub layer. Measurements of stem and canopy and small deadwood.
5×5	Sampling of biomass of herbaceous species and grasses, aboveground and roots, litter fall and debris for drying and weighing to determine live and dead biomass.

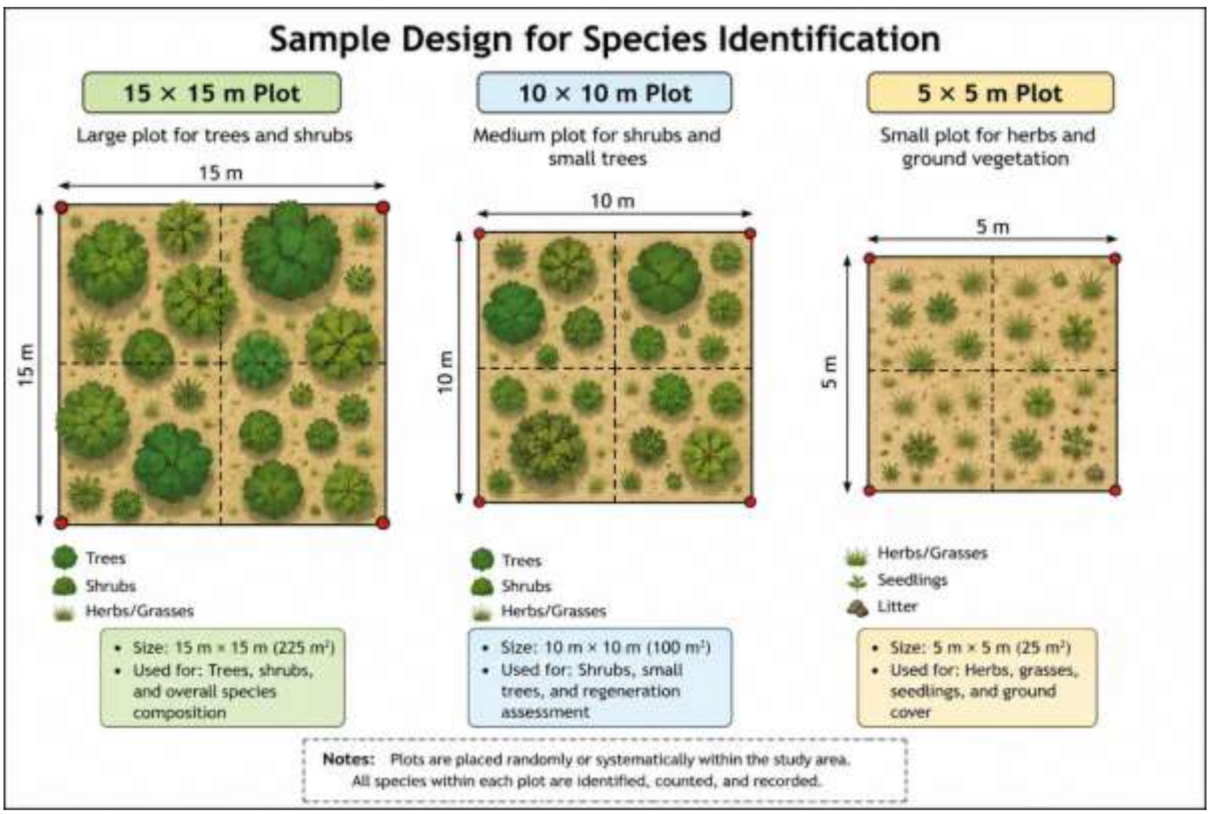


Figure 3.5 Sampling Design for species identification

3.4 Data Sources

To get the empirical data different techniques, both primary and secondary sources were used. Primary sources of data are first-hand information that was collected through Questionnaire, Key informant Interviews, Focus Group discussions. Whereas, secondary sources of data were used for literature review and for discussion parts collected through document review. The following documents such as; reports (at international, National, and Regional levels), thesis/dissertations was consulted. But to get relevant and empirical data, the researcher focus on primary sources of data.

3.5 Data Collection Instrument

3.5.1 Questionnaire Surveys

The questionnaires were developed based on the review of the literature and have incorporated both open-ended and close-ended questions. Questionnaires were used for 361 selected sample respondents to collect reliable and relevant data about the demographic data such as; age, sex, education, family size, socio-economic data, and the perception of the community about climate change in the study area. The questionnaires was prepared first in English and translate to the local language of the study area "Amharic" and distributed to the household heads.

3.5.2 Key Informant Interview

According to scholars, key informants are those who are considered to be experts/have special experience on a particular issue or topic for the researcher and interviewed repeatedly (Kothari, 2004). Natural Resource management experts, Agriculture officers worked at the district level, the Church administrators, biologists related to biodiversity conservation, ANRS Forest authority office employers and the aged person who live a long period of time at the study area considered as the key informant interviewee.

3.5.3 Focus Group Discussion

A focus group is a cost and time-effective method of collecting high-quality information. By allowing in-depth open-ended discussions and probing on the issue, this methodology provides for elaboration and consequently, a detailed analysis that incorporates all aspects and angles of the topic, leading to greater insight and understanding of the topic (Creswell, 1999). Individuals aged persons who live a long period of time and household heads in the study area. Hence, there were four FGD groups having six members for each and were used for the second objective.

Annual and monthly rainfall and temperature data were obtained from two sources. Long-term historical data were obtained from six gauge stations' (Finoteselam, Laybirr, Tachebirr, Genetabo, Wogaguanesa, Geray) from 1981-2022 for 41 years from the Ethiopian Meteorological Institute (EMI). The data obtained for the characterization of spatiotemporal variability and trend of rainfall and temperature. In addition to gauge stations' climate data also used for temperature and precipitation collected from NASA by the following website https://power.larc.nasa.gov/data-access-viewer/

3.6. Data Analysis Technique

The spatiotemporal variability and trends of rainfall and temperature in Jabitehinan Districts the annual and seasonal (winter, spring, summer and autumn) spatiotemporal variability and trends of rainfall were analyzed using the indices of Coefficient of variation (CV) and the Precipitation Concentration Index (PCI). The non-parametric Mann-Kendall (MK) test and Sen's Slope estimator were applied for trends and magnitude of rainfall and temperature. The non-parametric MK trend test was computed to analysis the annual and seasonal based (Winter, Spring, Summer and Autumn) rainfall and temperature. The MK test is widely applied to the most effective method in favour of statistically significant trend test detection in different climatological and hydrological time series applications (Ahmed *et al.*, 2014a). The relative strength of the MK trend test in time series data (trend magnitude) has been quantified using the non-parametric procedures of Sen's (1968) slope estimator. As noted by (Jain *et al.*, 2012a), the Sen's slope estimator is commonly used for determining the trend magnitude in hydro-meteorological time series. The observed annual and seasonal (winter, spring, summer and autumn) spatial variability and trends of rainfall, and temperature were also mapped using the spatial analysis tool (Inverse Distance Weighting, IDW) interpolation method. The IDW is a measure between neighboured stations for time series. It is more robust especially close to mountainous terrain where complex rain–orography interactions are considered (Ahrens, 2006). Inverse Distance Weighted, IDW average interpolation methods have been applied since this method is a simple, but the most commonly used, efficient and promising technique for estimation of missing data (Ahrens, 2006; Suhaila *et al.*, 2008).

Several bias correction techniques were developed to correct the bias, ranging from very simple to more complex methods, such as quantile mapping (QM), general quantile mapping (GQM), power transformation (PT), and linear scaling (LS) (Teutschbein *et al.*, 2012), 2012). They can be classified according to the degree of their complexity and simpler methods such as scaling factors and more sophisticated techniques such as probability mapping. Although the RCM climate variables' bias correction significantly improves hydrological modelling, there is a major drawback. All bias correction methods are based on the assumption of static model errors (Teutschbein *et al.*, 2012). This means that the correlation algorithm for current climate conditions and its parameters are considered valid even under the changing climate conditions.

Farmer's perception for climate variability and its impact by agro-ecological zone was analyzed as the following; numerous factors were hypothesized to affect households' perception to climate change and variability. In order to get essential information and insight into farmer's mitigation to climate change, looking at their perception on each climate attributes were quite important. Descriptive statistics were used to characterize farmer's perception on changes in long-term temperature, rainfall and other aspects. To analyze smallholder farmers perception to change in climate, further comparison were made correspondence with climate data recorded in Finote Selam Sub-station for 41 years for the period (1981-2022) by fitting a linear trend of annual means of temperature and rainfall. Making this trend in annual average temperature and rainfall a base for comparison, the perception of farmers was analyzed whether it was in line with or opposite to the linear trend fitted from Finote Selam Meteorological data. This has been done by asking household heads questions about their opinion on the direction of climate change on some attributes of climate change. Percentages were used to analyze the proportion of respondent in each level. Farmers who strongly agree and who simply agree were considered perceived the change while others not. Chi-square was employed to evaluate the importance of variation on evaluated variables between agro ecology (semi-arid, sub-tropical and temperate highland) at p-value < 0.05. The word-based approach was utilised to extract themes from the FGD and KII participants' responses and open-ended inquiries, which were subsequently coded for a straightforward count analysis ranking. Logistic regression model was employed to analyze determinants of farmers' perception of climate change and variability. A one-way ANOVA followed by Tukey's Post-Hoc test was performed to compare farmer's perception on climate change across the three agro-ecological zones. Statistical significance was set at the $p < 0.05$ level, with distinct letters assigned to the means indicating significant differences.

Plant biodiversity in the church forests was analyzed using standard diversity indices to assess species richness, evenness, and community composition. Biodiversity at the species level is commonly quantified by indices that integrate both the number of species present and their relative abundance within a given ecosystem, providing a more comprehensive understanding of ecological structure and function (Morris *et al.*, 2014). These indices are widely applied in ecological studies to evaluate patterns of species distribution and the degree of heterogeneity within plant communities.

One of the most difficult tasks during fieldwork could be the identification of species on the ground. As a result the researcher was used botanist, plant taxonomist, forest taxonomist, and indigenous knowledge by engaging the help of knowledgeable local people. These are people who are plant experts or have been working in the area long enough to have the ability to identify species using local and scientific names. Lastly if the identification of plant species beyond the above alternatives, the researcher were collected, pressed, dried and mounted then transported to the National Herbarium at Addis Ababa University for identification by referring (Beekle, 2007).

Biodiversity indices are widely used quantitative tools for assessing different dimensions of plant diversity within ecological communities. A diversity index provides a mathematical expression of species diversity by integrating both species richness (the total number of species present) and species abundance (the relative number of individuals per species) (Morris *et al.*, 2014). In general, ecosystems with higher species richness and more even distribution of individuals among species are considered more diverse(Chao *et al.*, 2014). Commonly used indices can be broadly categorized into richness indices, dominance indices, and information-based (entropy) indices, each capturing distinct aspects of community structure and composition (Magurran, 2003; Chao *et al.*, 2014; Morris *et al.*, 2014).

- ❖ Shannon Diversity Index
- ❖ Simpson Diversity Index
- ❖ Sorenson's Coefficient Index

Shannon Diversity Index= $-\sum_{i=1}^{s}$ pi Inpi

The Shannon index is an information statistic index which measures species diversity, species evenness and species diversity from randomly sampled (Spellerberg *et al.*, 2003). In the Shannon index, p is the proportion (n/N) of individuals of one particular species found (n) divided by the total number of individuals found (N), ln is the natural log, Σ is the sum of the calculations, and s is the number of species.

- ❖ Simpson Diversity Index

The Simpson index is a dominance index because it gives greater weight to common or dominant species. In this case, the presence of a few rare species with only a small number of individuals does not significantly affect the overall diversity (Reich *et al.*, 2001).

$$\text{Simpson Diversity Index (SDI)} = \frac{\sum n\,(n-1)}{\sum N\,(N-1)}$$

In the Simpson diversity index, **n** is the individuals of one particular species found, **N** divided by the total number of individuals found, **and Σ** is still the sum of the calculations. The result of Simpson index ranges from 0 to 1, with values close to 1 showing a community of many species with equally low abundances while numbers close to 0, express fewer species with one of them clearly dominant.

- Sorenson's Coefficient

In this index the researcher were Calculating community similarities (what the communities have in common in terms of species) help me to determine if I comparing species to species. Sorenson's coefficient gives a value between 0 and 1, the closer the value is to 1, the more the communities have in common. Complete community overlap is equal to 1; complete community dissimilarity is equal to 0 (Magurran, 2003). The equation is:-

$$\text{Sorenson's Coefficient (CC)} = \frac{2C}{S1+S2}$$

Where C is the number of species the two communities have in common, S1 is the total number of species found in community 1, and S2 is the total number of species found in community 2. Thus the above mentioned biodiversity index were computed by paleontological statistical software (Past software) version 4.03.

Density: It refers to the number of all individual plant species within the quadrates. According to Kent (2011), density is computed by converting the count from the sample plot to the hectare basis using the following formula:

$$\text{Density (D)} = \frac{\text{Number of individuals of a species in the sample}}{\text{Sample area in hectare}}$$

$$\text{Relative density (RD)} = \frac{\text{Number of individuals of a species}}{\text{Total number of individuals of all species}} *100$$

Frequency (F): It was calculated as the number of plots occupied by a given species per total number of plots laid out, more often as a percentage (Magurran, 2003).

Frequency (F) = Number of plots in which a species occur *100

Total number of plots laidout

$$\text{Relative frequency (RF)} = \frac{\text{Frequency of a species}}{\text{Sum of frequencies of all species}} * 100$$

Basal area (BA): It is the cross-sectional area of tree stems at breast height (1.3 m above ground level). Generally, it is a measure of dominance, which refers to the degree of coverage of species that occupies at ground level (Kent, 2011).

$$BA = \frac{\pi d2}{4}$$

Where: BA = Basal Area in m2ha−1, d = diameter at breast height (m), and π = 3.14.

Dominance (DO) = total cover or basal area of species A/area sampled.

$$\text{Relative Dominance (RDo)} = \frac{\text{Total basal area of a species}}{\text{Total basal area of all species}} * 100$$

Important Value Index (IVI): is useful to compare the ecological significance of species. It was calculated as the sum of relative dominance (RDo), relative density (RD) and relative frequency (RF) (Kent, 2011).

IVI = RD + RF + RDo

The phytogeographical comparisons of Awunt abo Monastry, Guanesa Medhanialem Monastry and Zengebal Giorgis church forests with each other were made using (Kent, 2011).

$$\text{Similarity coefficient (Ss)} = \frac{2a}{2a + b + c}$$

Where a = the number of species common to both habitats, b = number of species in the first habitat and absent from the second, c = number of species in the second habitat and absent from the first.

To assess the Carbon sequestration potential of church forest and implication for climate change mitigation were analyzed by Aboveground and Belowground Biomass estimation. The estimation of AGB in the forests is based on plot inventories that involve in the following three steps (Houghton *et al.*, 2001b; Bonorino *et al.*, 2002; Chave *et al.*, 2005a).

1. The selection and application of an allometric biomass function for the estimation of individual tree biomass,

2. The summation of individual tree AGB to estimate plot AGB, and

3. The calculation of an across-plot average to hectare based.

In this study, site-specific allometric equations were more accurate in predicting the forest biomass estimates on the local level as they take into account the site effects. According to the studies conducted by Asner *et al.* (2012), when biomass allometric models are not available for a given forest site, a simple height diameter allometry is required to estimate the biomass and carbon stocks accurately from plot inventories. Allometric equations given by WBISPP (2000) and the methodology for field data gathering prepared by FAO (PicardSaint-André *et al.*, 2012b) were used un-destructive allometric method, because in the church forest destructive method impossible as a result the researcher determine to use Woody Biomass Inventory and Strategic Planning Project (WBISPP) allometric method. The equations were developed based on the aboveground tree biomass for different tropical climatic/rainfall regions. The total annual rainfall obtained from a weather station close to the study sites were used to determine the allometric equation. The carbon stock estimated by the two equations was statistically compared.

The equations developed by Woody Biomass Inventory and Strategic Planning Project (WBISPP, 2000) for all woody species in different agro-ecological zone of Ethiopia were also used for estimating tree carbon stock and later to comparing with the results estimated according to Browns equation. The following equation was used:

AGB = (1.4277*DBH) + (0.0088*(DBH exp 3.0))

Where, AGB = Above Ground Biomass (kg/tree) and

DBH = Diameter of Brest Height (cm)

Tree biomass were converted to carbon stock (Friedlingstein *et al.*, 2022):

AGB Carbon Stock = AGB * 0.5

Where, AGB = Above Ground Biomass (kg/tree)

The below ground carbon stock were calculated by using the following formula:-

Root biomass is often estimated from root-shoot ratios (R/S) by taking 25% of aboveground biomass (Mokany *et al.*, 2006). The equation presented in (IPCC, 2006) were used to make estimates of root biomass in a standard manner for forests based on the knowledge of the above-ground biomass. The root biomass was converted in to root carbon stock by taking 25% of the root biomass.

Root Biomass = AGB x 0.25

Where, AGB = Above Ground Biomass (kg/tree)

The total carbon stock density was calculated by summing all the carbon pool stock densities using the following formula:

C Density = CAGTB + CBGTB

Where, C Density = Carbon Stock Density [Mg ha-1]

CAGTB = Carbon Stock in Above Ground Tree Biomass [Mg ha-1]

CBGB = Carbon Stock in Below Ground Tree Biomass [Mg ha-1]

Chapter Four

Spatio-temporal variability of temperature and rainfall in the Jabitehinan District in North West Ethiopia[1]

4.1 Introduction

Since rain-fed agriculture is the primary method of food production in the Horn of Africa where Ethiopia is located the region is particularly vulnerable to climate variability. Studies by Blein *et al.* (2017) and Khatri *et al.* (2023) highlight that rising temperatures and inconsistent precipitation are expected to reduce crop yields and overall agricultural productivity. Ethiopia features a wide range of agroclimatic zones, with rainfall and temperature distributions varying from semi-arid to humid and warm conditions (Regassa *et al.*, 2010). The mean annual rainfall also shows significant variation: while the southwestern highlands receive over 2,000 mm, the southeastern and northwestern plains get less than 300 mm (MinistryofWater, 2016). Similarly, the annual mean temperature varies greatly, ranging from over 25°C in the lowlands to below 15°C in the highlands (Degefu *et al.*, 2014). Ethiopia exhibits diverse agroclimates, with mean annual rainfall ranging from over 2,000 mm in the southwestern highlands to less than 300 mm in the southeastern and northwestern plains, and highly variable temperatures from semi-arid to humid and warm conditions (Regassa *et al.*, 2010). According to (Regassa *et al.*, 2010); Kew *et al.* (2017), it is over 25^0C in the lowlands and less than 15^0C in the highlands.

Ethiopia experiences four main seasons locally known as winter, spring, summer, and autumn. The dry winter season typically spans from December to February. The major rainy season locally called Kiremt occurs from June to August, while the shorter rainy seasons in spring and autumn occur from March to May and from September to November, respectively (Gissila *et al.*, 2004; Riddle *et al.*, 2008; Regassa *et al.*, 2010; Kew *et al.*, 2017).

---

[1]Birhanie, *et al.* (2025) Spatio-temporal variability of Temperature and rainfall in the Jabitehinan District in North West Ethiopia Indonesian Journal of Geography 57(2) https://doi.org/10.22146/ijg.102013

However, there is significant variability in seasonal rainfall distribution across the country (Riddle *et al.*, 2008; Kew *et al.*, 2017). The timing and intensity of the two rainy seasons summer, spring, and autumn directly affect agricultural productivity (Teyso *et al.*, 2016; Tessema *et al.*, 2019; AfricanDevelopmentBank, 2024). Rain-fed agricultural activities are closely linked to rainfall patterns, delays in the onset of rain or early cessation are major contributors to crop failure (Tessema *et al.*, 2019).

In the northern and eastern regions of Ethiopia, insufficient rainfall poses a similar threat, contributing to decreased crop and livestock productivity and exposing farm households to persistent food insecurity (Dinku, 2010; Asfaw *et al.*, 2018). Rainfall variability is cited as a key factor contributing to poverty, with approximately 30% of the Ethiopian population living below the poverty line (Regassa *et al.*, 2010; Ndaruzaniye, 2011). These challenges are especially acute in the area under study, where erratic temperature and precipitation patterns frequently lead to agricultural failure. Smallholder farmers are particularly vulnerable, as fluctuations in temperature and rainfall often result in crop loss and livestock mortality (NMSA, 2007). The impacts of climate variability and extremes in Ethiopia are among the most widely documented in both media and scientific literature (Gautam *et al.*, 2009).

Given this context, a comprehensive and detailed study is essential to understand trends in key meteorological variables at a fine spatial scale. Such analysis supports informed decision-making in sensitive sectors such as agriculture (Esayas *et al.*, 2019). Research indicates that examining the spatial and temporal characteristics of rainfall and temperature is critical for urban and agricultural planning (Mehmet, 2015), flood risk analysis, water resource assessments, and evaluating the impacts of climate change (Alemu, 2019). This study focuses on the northwest highland region of Ethiopia, where diverse topography results in marked spatial variability and distinct climatic patterns. These differences are evident in both seasonal and annual rainfall and temperature averages (Ademe *et al.*, 2020). The observed variability across seasons has significantly influenced the performance of agriculture, the region’s dominant economic sector (Esayas *et al.*, 2019).

Rainfall and temperature variability and trends were documented by many scholars in Ethiopia (Woldeamlak Bewket *et al.*, 2007; Abtew *et al.*, 2009; Bewket, 2009; Ayalew *et al.*, 2012; Jain *et al.*, 2012b; Ahmed *et al.*, 2014b; IPCC, 2014b; MinistryofWater, 2016; Asfaw *et al.*, 2018; Ademe *et al.*, 2020; Alemayehu *et al.*, 2020b; Mekonen *et al.*, 2020; Alemayehu *et al.*, 2022; Wassie *et al.*, 2022; IPCC, 2023). These studies were shown inconsistent results of seasonal and annual climate variability and trends mainly on rainfall variability and trend. The inconsistency might have originated from differences in spatial extent, study periods and geographic location. This study also believed that these differences might originate from the mountainous nature of the country that needs to investigate at local and/or micro-levels. In this regard, reports and scientific works such as (IPCC, 2000b; Easterling *et al.*, 2007; Bewket, 2009) evidently pointed out that local scale spatiotemporal rainfall and temperature variability and trends in many parts of Ethiopia remain unknown and needs scientific investigation at the local level. More specifically, Gissila *et al.* (2004) noted that though analyses of spatiotemporal rainfall and temperature variability and trends at national and regional levels are imperative, analysis at the local level is equally important for water management, food security analysis, and disaster risk management. This study has two research questions: 1) what are the trends in rainfall and temperature (maximum, minimum, and mean) across different seasons (spring, summer, autumn, and winter) and on an annual basis in the Jabitehinan District? 2) How does the spatial variability of rainfall and temperature manifest across different areas of the Jabitehinan District, as determined using the Inverse Distance Weighted (IDW) spatial analysis method? The authors contribute empirical evidence, methodological rigor, and practical recommendations that together support climate resilience in agriculture and resource management.

An international reader of the journal can gain several important insights from this study on the spatiotemporal variability of temperature and rainfall in the Jabitehinan District, northwest Ethiopia. Broader Understanding of Climate Change Impacts in Vulnerable Regions, the study offers a clear example of how climate change is manifesting at a local scale in sub-Saharan Africa. It adds to the global discourse by providing empirical data from a region where agriculture is highly sensitive to climate variability, but where such detailed analyses are often underrepresented in the literature. Methodological Application in Data-Scarce Settings, by using robust statistical tools like Sen's slope estimator, the Mann-Kendall test, and the Inverse Distance Weighted (IDW) method, the paper demonstrates how meaningful climate trend analyses can be conducted even in regions with limited meteorological infrastructure, offering a replicable model for similar regions globally. Insight into Rainfall and Temperature Trends over Time, international readers can observe long-term, seasonal, and decadal changes in rainfall and temperature in a semi-arid region. These changes are quantified, showing trends such as temperature increases and rainfall reduction, which are critical indicators of climate risk. Agricultural and Policy Implications, the paper underscores the direct link between climate trends and agricultural productivity, especially for rain-fed farming systems, which are prevalent in many developing regions. The findings inform climate-smart agricultural strategies and adaptation planning, relevant to policymakers, development agencies, and climate resilience practitioners worldwide. Relevance to Similar Agro-Ecological Zones Globally, the study's conclusions are not only relevant to Ethiopia but also to other regions with similar topographic and climatic conditions. It contributes comparative data that can aid in regional and global climate resilience strategies.

While many studies examine global or national climate trends, this research provides a detailed, district-level analysis of long-term temperature and rainfall patterns. Such localized studies are relatively rare but crucial for effective climate adaptation. The study combines Sen's slope estimator, the Mann-Kendall test, the Precipitation Concentration Index (PCI), and Inverse Distance Weighted (IDW) spatial interpolation. This integrated approach strengthens the reliability of the analysis and adds depth to the understanding of both temporal and spatial variability. Unlike most climate studies that focus solely on temporal changes, this research maps the spatial distribution of rainfall and temperature across different zones within the district. This spatial perspective adds a new layer of insight, highlighting climate disparities within relatively small geographic areas. The study goes beyond reporting trends by explicitly linking climate variability to agricultural productivity and resource management. It stresses the need for climate-smart practices, which offers a practical direction for future adaptation measures and policy decisions.

Therefore, this study aims to examine the trends and variability of seasonal and annual rainfall and temperature in the district, as well as to illustrate their spatial distribution and variation. The findings were offer valuable insights for informed decision-making and strategic planning, supporting the implementation of effective measures to reduce the impacts of climate variability on the environment. This is vital for promoting sustainable economic development, particularly in climate-sensitive sectors like agriculture.

4.2 Data Sources and Data Analysis

Gridded monthly precipitation data for the Greater Horn of Africa was sourced at a spatial resolution of 0.10° x 0.10°, offering a comprehensive and precise dataset. In contrast, temperature data with a resolution of 0.50° x 0.50° was obtained from the Climate Research Unit (CRU) Time-Series (TS) dataset. Additionally, the Ethiopian National Meteorological Agency (ENMA) – West Amhara Meteorological Service Centre in Bahir Dar provided long-term, station-based historical monthly meteorological data covering the period from 1981 to 2022.

To enhance the accuracy of the gridded datasets, statistical bias correction techniques such as quantile mapping were employed. These methods were used to adjust the gridded data to more closely align with the station-based observations.

The study utilized data from six meteorological gauge stations characterized by high data quality, long-term records, and good spatial distribution across the region. As discussed in the following sections, various statistical indicators and tests were applied to analyze the spatiotemporal variability and trends in rainfall and temperature. In particular, the coefficient of variation (CV) and the Precipitation Concentration Index (PCI) were used to assess the temporal variability of rainfall.

The temporal variability of rainfall was displayed using the coefficient of variation.

Where: mean, standard deviation, and coefficient of variation (CV, σ). Therefore, a coefficient of variation of less than 20 indicates reduced variability, a coefficient of variation between 20% and 30% indicates moderate variability, and a coefficient of variation larger than 30% indicates significant rainfall variability (Alemayehu *et al.*, 2020a). The concentration of yearly and seasonal rainfall was shown using the Precipitation Concentration Index (PCI).

$$PCI_{annual} = \frac{\sum_1^{12} = 1pi2}{(\sum_{1=1\,pi)}^{12} 2} \quad (x\ 100) \quad \ldots\ldots (1)$$

$$PCI_{Seasonal=} \frac{\sum_{1=1\,pi}^{4} 2}{} \quad (x\ 33.3) \quad \ldots\ldots (2)$$

$$(\sum_{1=1\,pi)}^{4} 2$$

Where: pi is the monthly rainfall in i^{th}

Sen's Slope Estimator and the Mann-Kendall (MK) Test: Sen's Slope estimator and the non-parametric Mann-Kendall (MK) test were used to examine the patterns and amounts of temperature and precipitation. In particular, the annual and seasonal rainfall and temperature data were evaluated using the MK trend test. In several climatological and hydrological time series applications, the MK test is frequently utilised as the most efficient technique for statistically significant trend test identification (NMSA, 2007; Ademe *et al.*, 2020; Alemayehu *et al.*, 2022). Additionally, the MK test is preferred over other tests since its procedures are less sensitive to outliers or robust against the influence of extremes (NMSA, 2007); can test trends in a time series without requiring normality or linearity, which is a distribution-free test (Alemayehu *et al.*, 2022). As a result, the World Meteorological Organisation strongly advises against using it generally (Alam *et al.*, 2017). The MK test is used to determine whether temperature variability and rainfall have a statistically significant or non-significant trend (Jain *et al.*, 2012b). According to (Suryabhagavan, 2017), a positive value denotes an increasing trend while a negative value denotes a decreasing trend over time.

The selection of Sen’s slope estimator and the Mann-Kendall test was driven by the specific goals of this study to analyze the trend and magnitude of changes over time in a reliable, robust, and non-parametric way. Both methods are widely used in environmental and climate studies, especially when dealing with time series data that may not follow a normal distribution or where data may exhibit outliers, skewness, or non-linearity.

Sen’s Slope: This method was chosen to estimate the magnitude of the trend because it is a non-parametric approach that is less sensitive to outliers than traditional linear regression. It provides a robust estimation of the slope of the trend, especially useful for time series data with potential irregularities. Sen’s slope is particularly appropriate when the data is noisy or non-linear, as it calculates the median of all possible pairwise slopes between data points, making it resistant to extreme values that could distort the results.

Mann-Kendall Test: The Mann-Kendall test was selected to assess the statistical significance of the trends detected by Sen's slope. It is a non-parametric test that evaluates whether there is a monotonic increasing or decreasing trend over time. This method is advantageous because it does not require the data to meet assumptions of normality and can handle both seasonal and non-seasonal data effectively. The test also provides a clear indication of whether trends are statistically significant, which is critical in understanding whether observed changes are likely due to real phenomena or simply random variation.

The following formulas were used to calculate the MK statistic S, its variance, and the related standard normal test statistic Z:

$$\sum_{i=1}^{N-1} \quad \sum_{j=i+1}^{N} sgn(xj - xi) \qquad \ldots\ldots. (3)$$

Where: N is the number of data points; X_i and X_j are the time series observations.

Assuming $(x_j - x_i) = \theta$, the value of sgn (θ) is computed from:

$$\text{Sgn } (\Theta) = \begin{cases} +1 \ldots \ldots . \theta & > 0 \\ 0 \ldots \theta & = 0 \\ -1 \ldots . . . \theta & < 0 \end{cases} \qquad \ldots\ldots. (4)$$

Under the hypothesis of independent and randomly distributed variables, for large samples (n $\geq$10), the σ statistic is approximately normally distributed, with zero mean and variance as:

$$\sigma 2 = \frac{n(n-1)(2n+5)}{18} \qquad \ldots\ldots. (5)$$

Thus, the distribution of the standardized normal deviate (Z-statistics) will subsequently be computed as:

$$\text{Z} = \begin{cases} S - 1/\sigma & if\ S>0 \\ 0 & if\ S=0 \\ S + 1/\sigma & if\ S<0 \end{cases} \qquad \ldots\ldots. (6)$$

As previously mentioned rising trends are denoted by a positive Z value and falling trends by a negative Z value. Similarly, trend magnitude has been measured using Sen (1968) non-parametric slope estimator processes in order to assess the relative strength of the MK trend test in time series data. Sen's slope estimator is frequently employed to ascertain the trend magnitude in hydro-meteorological time series, as mentioned by (Tessema *et al.*, 2019). Because of its comparatively low sensitivity to extreme values, it is a robust estimator (Chattopadhyay *et al.*, 2016). The slopes of each pair of data are calculated using (Chakraborty *et al.*, 2013) in order to provide an estimate of the slope bi, as follows:

$$\text{bi} = \frac{xj-xi}{j-i}, i = 1,2,3, \ldots N, j > i \qquad \ldots\ldots (7)$$

Where: xj and xi are data values at times j and i. The Sen's estimator of the slope is the median N values of bi:

$$\text{b} = \begin{cases} b(N+1)/2 & if\ N\ is\ odd \\ 0.5[bN/2 + b(N+2)/2] & if\ N\ is\ even \end{cases} \qquad \ldots\ldots (8)$$

A positive value of b indicates an increasing value with time while a negative of b indicates a decreasing value with time.

Inverse Distance Weighting (IDW): Although gridded data were used in this study, Inverse Distance Weighting (IDW) interpolation was employed to refine the spatial resolution and fill in gaps where data points were sparse or unevenly distributed. The original gridded dataset did not provide adequate spatial coverage at the scale required for our analysis, particularly in regions with complex topography or variable data density. IDW was chosen due to its simplicity, transparency, and effectiveness in scenarios where spatial autocorrelation is assumed that is, where nearby points are more likely to have similar values.

The choice of IDW over other interpolation methods (e.g., kriging or spline) was based on its computational efficiency, especially in large datasets. Furthermore, preliminary tests showed IDW performed comparably well in terms of accuracy for this dataset.

To validate the IDW interpolation, a cross-validation procedure was carried out using a subset of observed data. This involved removing a portion of known data points, performing the interpolation, and then comparing the interpolated values against the actual data. The resulting root mean square error (RMSE) and mean absolute error (MAE) were within acceptable limits, indicating that IDW provided a reasonable approximation for the spatial patterns present in the data (Ahrens *et al.*, 2006). For the purpose of identifying and calculating variability and trends (time series) of annual and seasonal rainfall and temperature values, the XLSTAT 2014 programme and Excel spread sheet were utilised. The trend's magnitude was also discovered using Sen's approach. Temperature and rainfall data were subjected to a geographical trend analysis using Geographic Information Systems (GIS version 10.1).

4.3 Results and Discussions

4.3.1 Temporal variability of rainfall

The study areas long-term mean annual rainfall, as indicated in Table 4-1, was 1000.9 mm, with an 87.2 standard deviation and an 8.7% coefficient of variation. With a standard deviation of 32.77 and a coefficient of variation of 3.28%, the decadal mean rainfall was 998.48 mm. The years with the lowest mean annual rainfall (674.1 mm) and the greatest (1251.9 mm) were 1916 and 1984, respectively. Spring produced 23% of the annual total rainfall, whilst summer contributed roughly 68.4%. In the Woleka sub-basin of South Wollo, Asfaw *et al.* (2018) reported a similar study showing that the summer and spring seasons provide 74.4% and 13% of the rainfall, respectively. Similarly, research in the Amhara Region (Ayalew *et al.*, 2012) and the Upper Blue Nile basin (Abtew *et al.*, 2009) found that the summer season accounts for the largest portion of the yearly rainfall total. Numerous more studies (UNFCCC, 2007b; Asfaw *et al.*, 2018; Alemayehu *et al.*, 2020b) showed that in many places of Ethiopia, the spring season contributes significantly less (5%–30%) to the total annual rainfall than the summer season (64%–85%).

Table 4. 1 Rainfall trend analysis by seasonal, and MK test (1981-2022)

Variable	Minimum	Maximum	Mean	Std. deviation	CV (%)	MK Test	Sen's Slope
winter	0.000	51.267	9.991	11.496	115.060	-0.057	-2
Spring	22.853	198.633	84.797	37.314	44.003	0.111**	4
summer	181.057	478.127	338.166	72.047	21.305	-0.277**	-10
autumn	38.673	210.937	118.729	43.250	36.427	-0.253**	-9
Annual	901.760	2515.430	1655.051	382.931	23.137	-0.111**	-4

** is statistically significant when P is less than 0.05.
Source Ethiopian Meteorological Agency (2022)

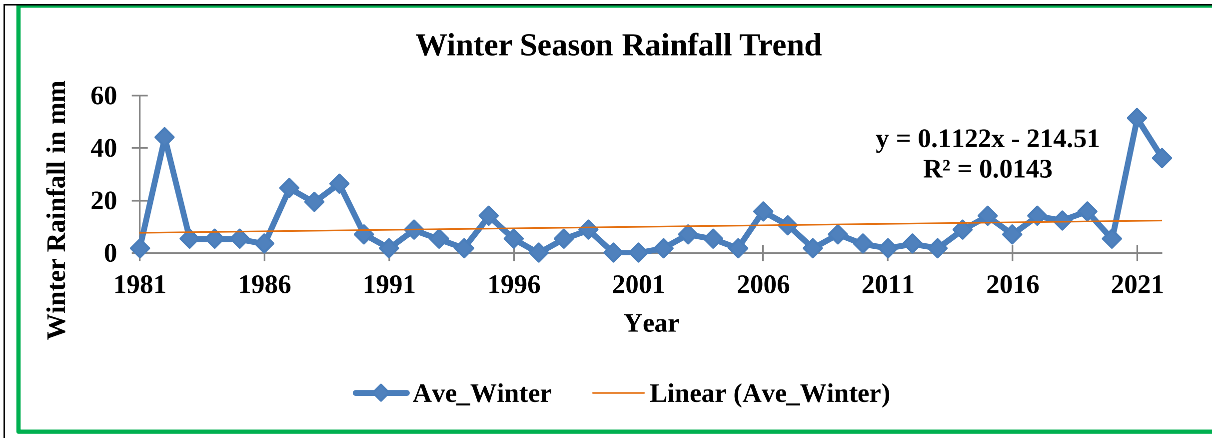
The coefficient of variation (CV) can be used to evaluate the variability of rainfall. Rainfall variability is classified as low when CV is less than 20, moderate when CV is between 20 and 30, and high when CV is greater than 30 (Hare, 2003). The winter season (December, January, and February) had a substantially larger coefficient of variation (115.0604%) than the summer season (June, July, and August), which had a CV of 21.30%. Research conducted in Ethiopia's Amhara Region (Bewket, 2009; Ayalew *et al.*, 2012; Rosell, 2013) revealed comparable findings, namely that the winter season's CV was greater and more unpredictable than the summer season's. The Mann-Kendall (MK) test and Sen's slope were used to detect and quantify trends in seasonal and annual rainfall. There is a slight decreasing trend in winter rainfall, but it is not statistically significant. The variability is very high (CV = 115.06%), indicating inconsistent patterns across years. A statistically significant increasing trend in spring rainfall is observed. The positive Sen's slope indicates an average increase of 4 units per year, suggesting that spring rainfall is becoming more abundant. A significant decreasing trend is detected in summer rainfall. The negative Sen's slope shows a reduction of about 10 units per year, which may impact water availability during the hottest season. Autumn also shows a significant decreasing trend in rainfall, with a drop of around 9 units per year. This could have implications for post-monsoon agriculture or hydrology. Overall, annual rainfall is declining at a statistically significant rate, with an average decrease of 4 units per year. Table 4.2 illustrates that, for the years 1981 to 2022, the annual PCI was predominantly characterised by a high proportion of erratic rainfall distribution (55.4%) over the observed years. While the spring and autumn seasons exhibit high irregular rainfall distribution and very high irregular rainfall distribution (49.5%) and (42.3%) of the seasons, respectively, whereas the summer season belongs to low variability rainfall distribution (17.4%) (Table 4-2). Similar findings are reported by (Bewket, 2009; Ayalew *et al.*, 2012; Asfaw *et al.*, 2018), showing that the summer months have higher concentrations of rainfall.

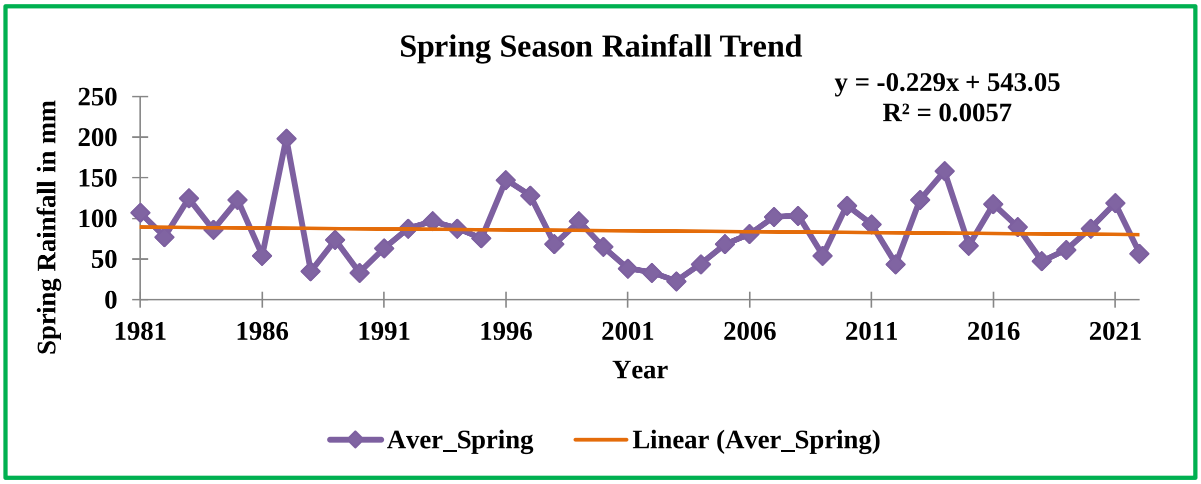
Table 4. 2 Precipitation Concentration Index (PCI) per season (winter, spring, summer, autumn, and annual) for 1981–2022

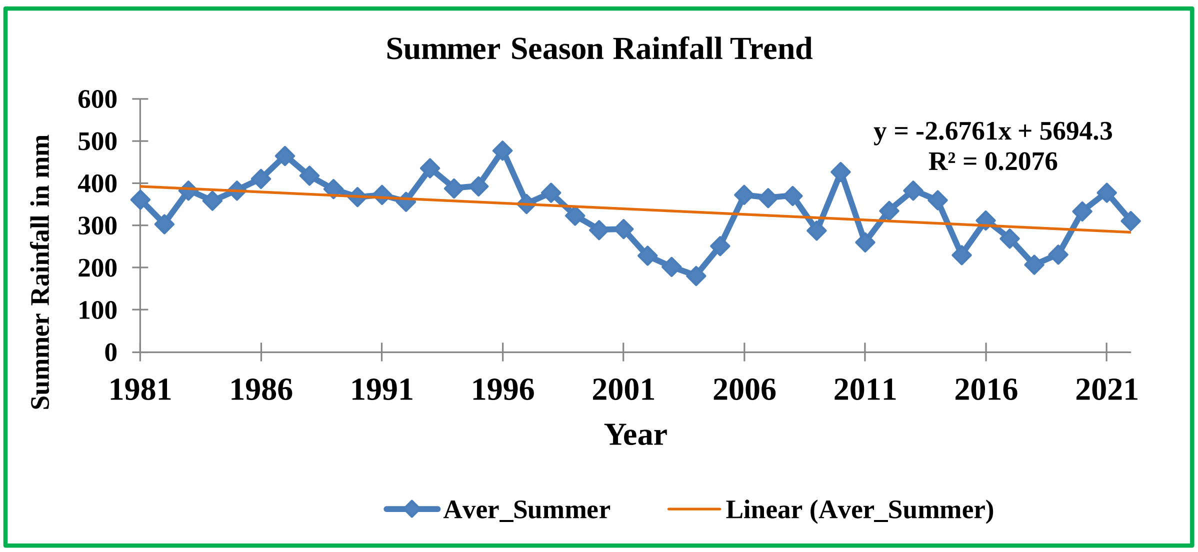
PCI Index (%)	Description	Observation seasons (%)				
		Winter	Spring	Summer	Autumn	Annual
<10	Uniform rainfall distribution/low concentration	-	-	-	-	-
10-15	Moderate rainfall distribution	-	-	-	-	-
16-20	High concentration/irregular rainfall distribution	-	49.5	17.4	-	55.1
>21	very high concentration/ irregular rainfall distribution	79.3	-	-	42.3	-

4.3.2 Trends of rainfall

With the exception of May and June, the Mann-Kendall test result showed a statistically significant declining trend in rainfall, as shown in Table 4-1. Additionally, the results showed that seasonal (winter, summer, and autumn) and annual rainfall displayed a significant decreasing trend, while spring season rainfall showed a non-significant decreasing trend (Wagesho *et al.*, 2013; Asfaw *et al.*, 2018; Tessema *et al.*, 2019). However, a number of researchers indicate statistically non-significant trend results (Seleshi *et al.*, 2004; McSweeney *et al.*, 2008; Suryabhagavan, 2017). For winter, spring, summer, autumn, and annual rainfall, respectively, the regression coefficients also showed declining trends at the rates of 0.112mm/year, -0.229mm/year, -0.676mm/year, -0.844mm/year, and -10.912mm/year (Figure 4.1). Rainfall reduction exhibited variations among winter, spring, summer, autumn and yearly at a rate of 0.014mm, 0.005mm, 0.207m and m 0.057mm, and 0.0122 correspondingly. The decrease in yearly and summer rainfall, however, is not determined to be substantial. A similar outcome was found by (Jury *et al.*, 2013) in the decrease of yearly rainfall at a rate of -0.4mm/year.


Winter Season Rainfall Trend
Winter Rainfall in mm
60
40
20
0
1981
1986
1991
1996
2001
2006
2011
2016
2021
Year
y = 0.1122x - 214.51
R² = 0.0143
Ave_Winter
Linear (Ave_Winter)


Spring Season Rainfall Trend
Spring Rainfall in mm
250
200
150
100
50
0
1981
1986
1991
1996
2001
2006
2011
2016
2021
Year
y = -0.229x + 543.05
R² = 0.0057
Aver_Spring
Linear (Aver_Spring)


Summer Season Rainfall Trend
Summer Rainfall in mm
600
500
400
300
200
100
0
1981
1986
1991
1996
2001
2006
2011
2016
2021
Year
y = -2.6761x + 5694.3
R² = 0.2076
Aver_Summer
Linear (Aver_Summer)

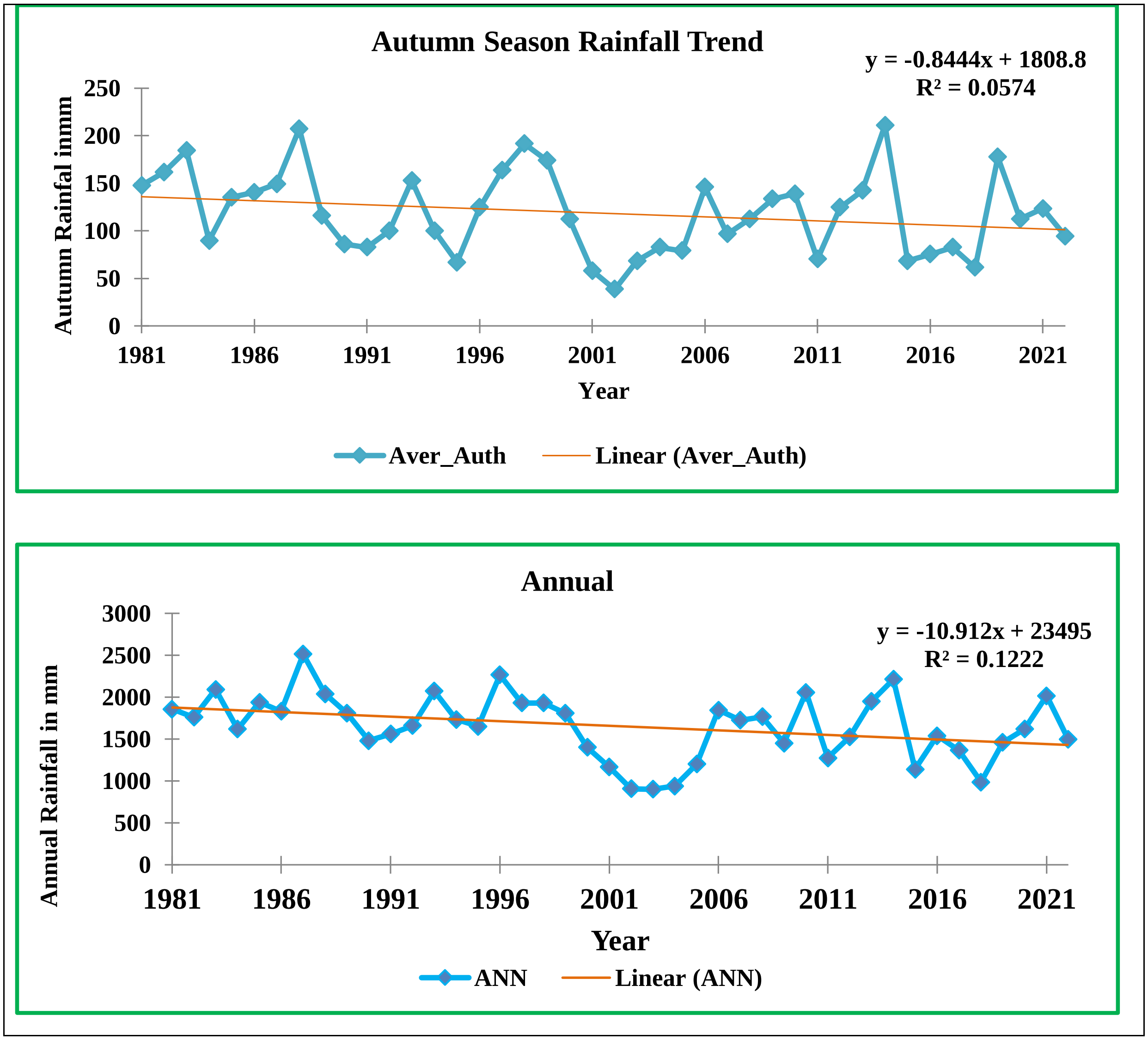


Figure 4. 1 Winter, Spring, Summer, Autumn and annual rainfall trends

4.3.3 Temporal variability and trends of temperature

To investigate the temporal variations and trends, the mean seasonal minimum, maximum, and annual temperature data for the years 1981–2022 were shown (Figure 4.2).

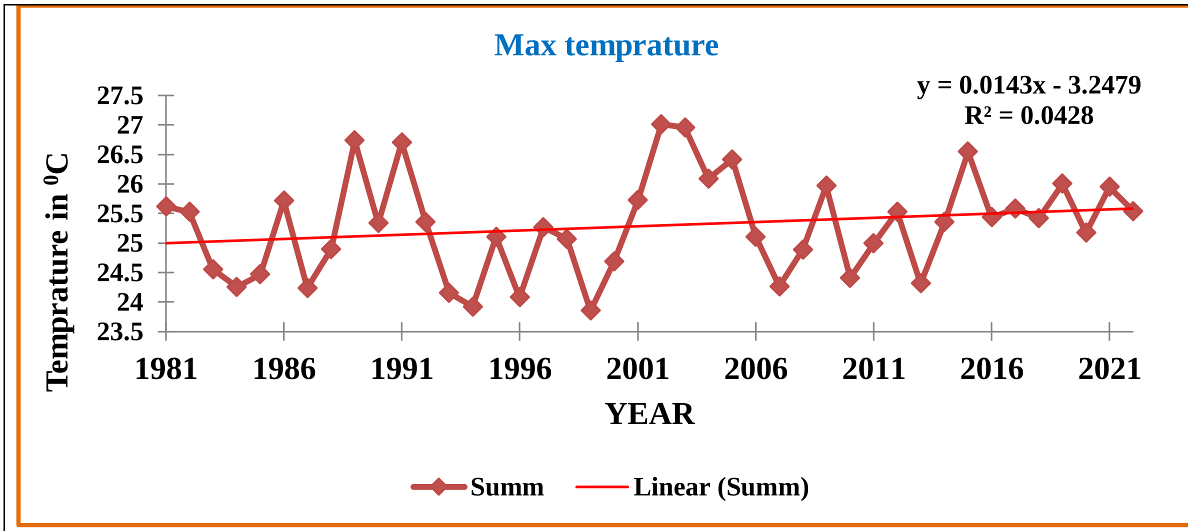
The research area's lowest temperature was 23.5^0C, its highest temperature was 34.8^0C, and its yearly average was 33.8^0C (Figure 4.2). The yearly average, maximum, and lowest temperature regression coefficients indicated an increasing trend at 0.014^0C, 0.029^0C, and 0.037^0C, respectively. The average temperature for the winter, spring, summer, autumn, and decadal regression coefficient results all exhibited an increasing trend at rates of 0.049^0C, 0.039^0C, and 0.014^0C, 0.029^0C and 0.037^0C per decade, respectively.

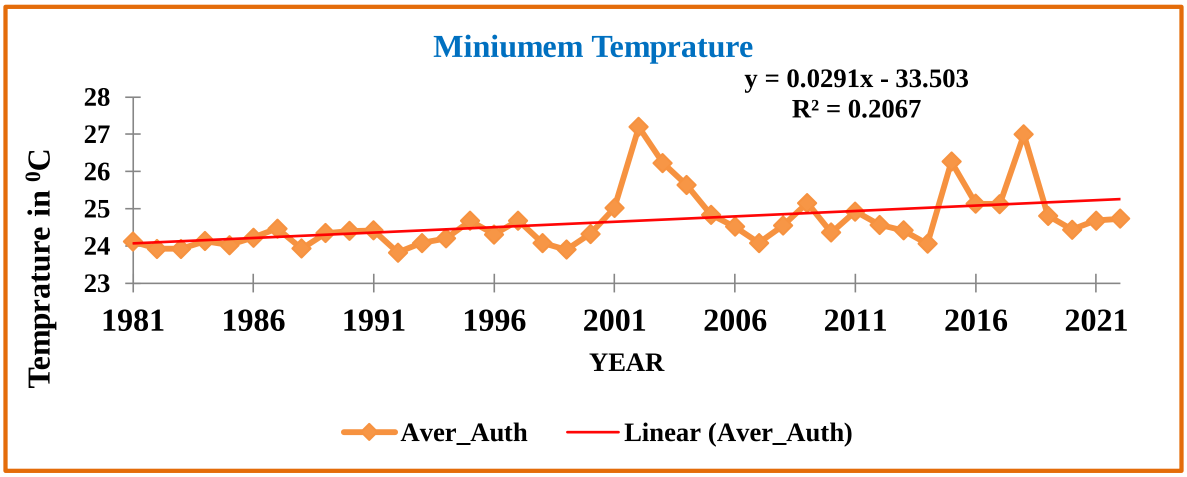
More specifically, since the 2000s, there has been a sudden rise in temperature. In this case, it was discovered that the minimum temperature increased more quickly than the maximum. The rate of annual average, winter, spring, summer, and autumn fall temperature has therefore grown by 0.189^0C, 0.215^0C, 0.184^0C, 0.042^0C, and 0.206^0C, respectively, over the last forty years (1981–2022). According to (McSweeney *et al.*, 2008; Asfaw *et al.*, 2018), these findings were supported. They came to the conclusion that many regions of Ethiopia have been seeing an increase in the annual, maximum, and minimum temperatures throughout all seasons.

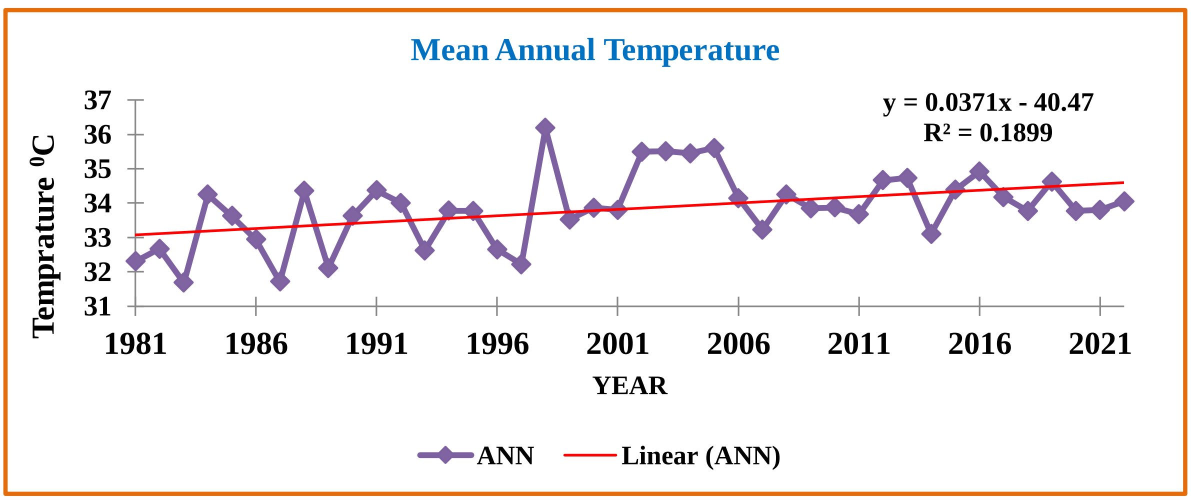
Table 4. 3 Seasons and annual MK trend test result of temperature (1982-2022)

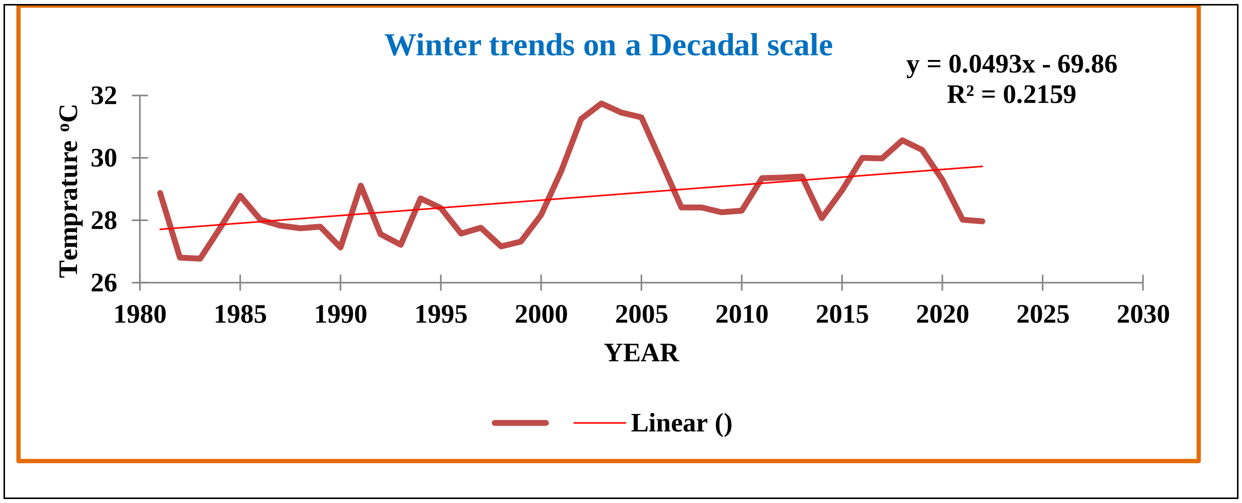
Seasons	Minimum	Maximum	Mean	Std. deviation	MK Test	Sen's Slope
Winter	26.767	31.740	28.820	1.300	0.389	14
Spring	30.507	34.880	32.774	1.126	0.500	18
Summer	23.850	27.010	25.285	0.845	0	0
Autumn	23.508	27.197	24.659	0.784	0.556	20
Annual	31.68	36.180	33.835	1.045	0.500	18

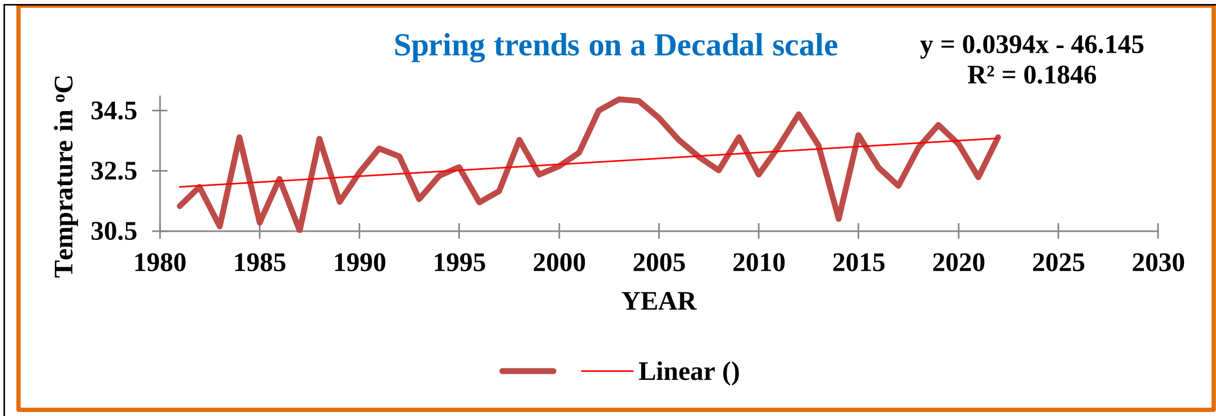
Source: Ethiopian Meteorological Agency (2022)

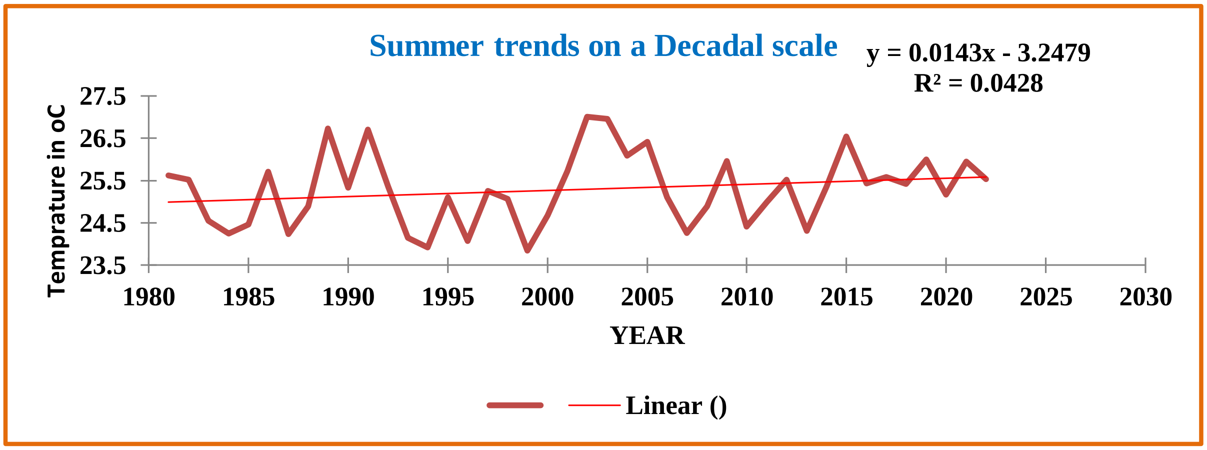

Max temprature
y = 0.0143x - 3.2479
R² = 0.0428
27.5
27
26.5
26
25.5
25
24.5
24
23.5
Temprature in 0C
1981
1986
1991
1996
2001
2006
2011
2016
2021
YEAR
Summ
Linear (Summ)

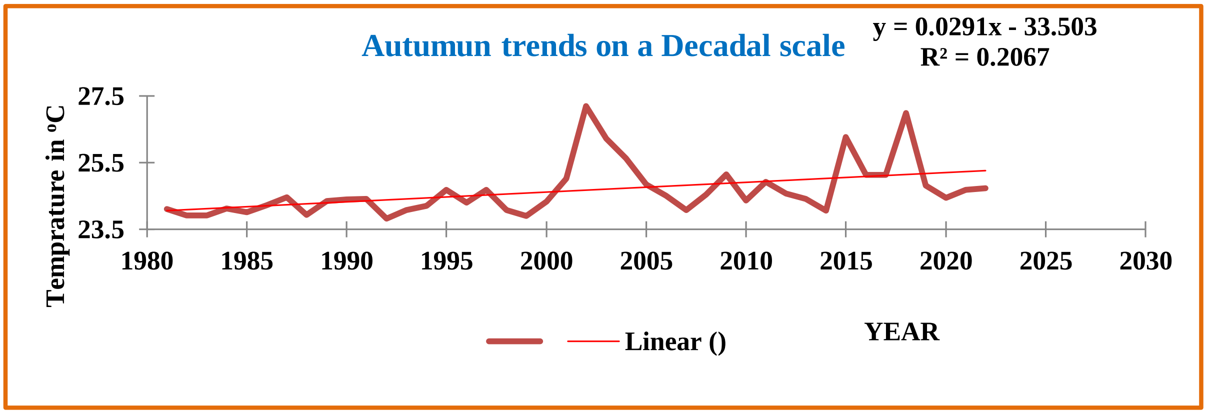

Miniumem Temprature
y = 0.0291x - 33.503
R² = 0.2067
28
27
26
25
24
23
Temprature in 0C
1981
1986
1991
1996
2001
2006
2011
2016
2021
YEAR
Aver_Auth
Linear (Aver_Auth)


Mean Annual Temperature
y = 0.0371x - 40.47
R² = 0.1899
37
36
35
34
33
32
31
Temprature 0C
1981
1986
1991
1996
2001
2006
2011
2016
2021
YEAR
ANN
Linear (ANN)


Winter trends on a Decadal scale
y = 0.0493x - 69.86
R² = 0.2159
Temprature °C
32
30
28
26
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
YEAR
Linear ()


Spring trends on a Decadal scale
y = 0.0394x - 46.145
R² = 0.1846
Temprature in ºC
34.5
32.5
30.5
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
YEAR
Linear ()


Summer trends on a Decadal scale
y = 0.0143x - 3.2479
R² = 0.0428
Temprature in oC
27.5
26.5
25.5
24.5
23.5
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
YEAR
Linear ()


Autumun trends on a Decadal scale
y = 0.0291x - 33.503
R² = 0.2067
Temprature in ºC
27.5
25.5
23.5
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
Linear ()
YEAR

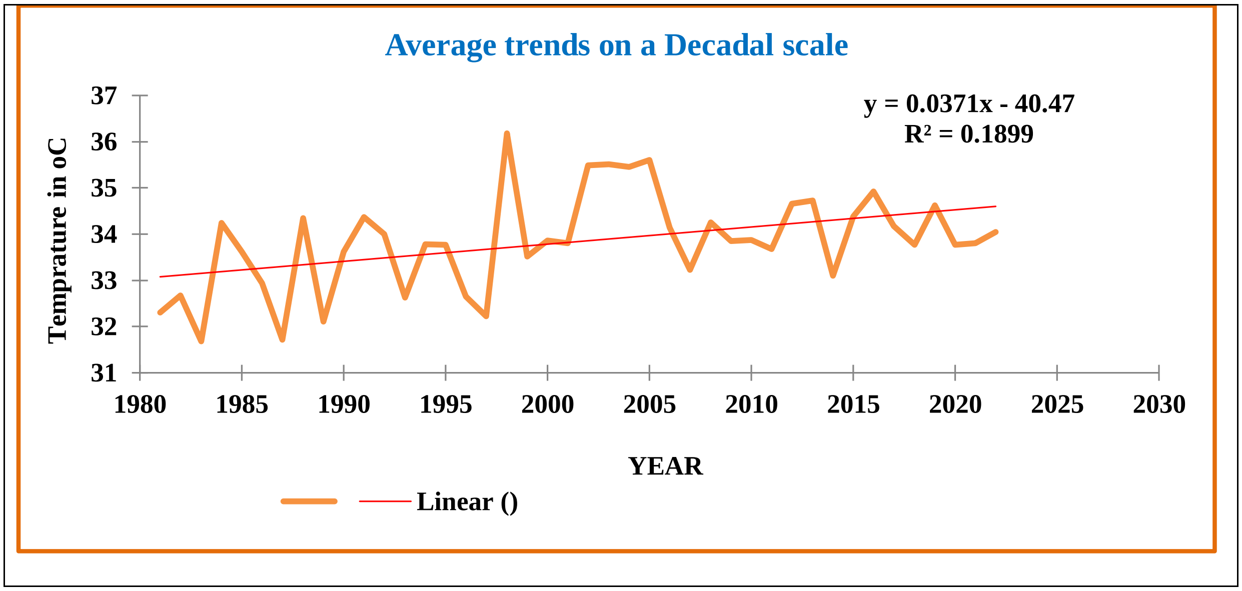


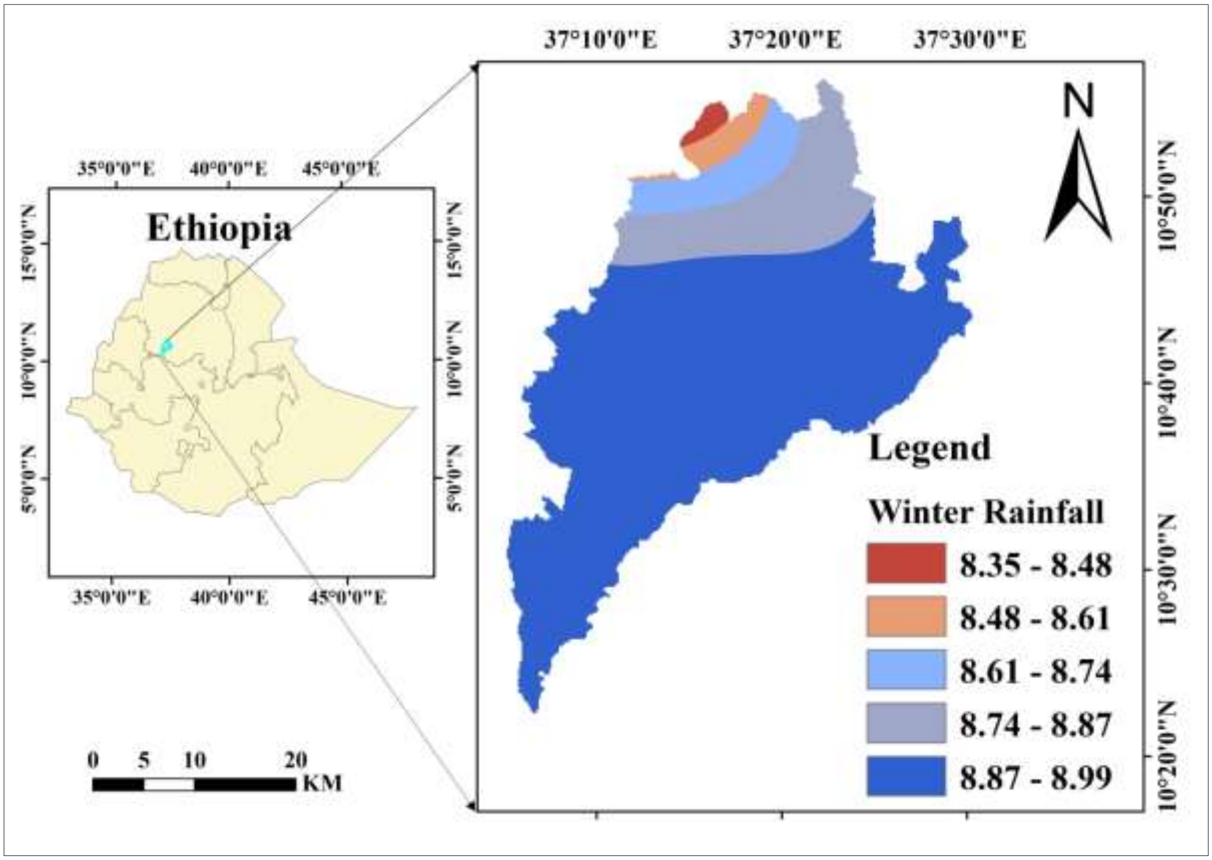
Figure 4. 2 Decadal trends of winter, spring, summer, autumn and average temperature (1981-2022)

4.4 Spatial variability and trend of rainfall

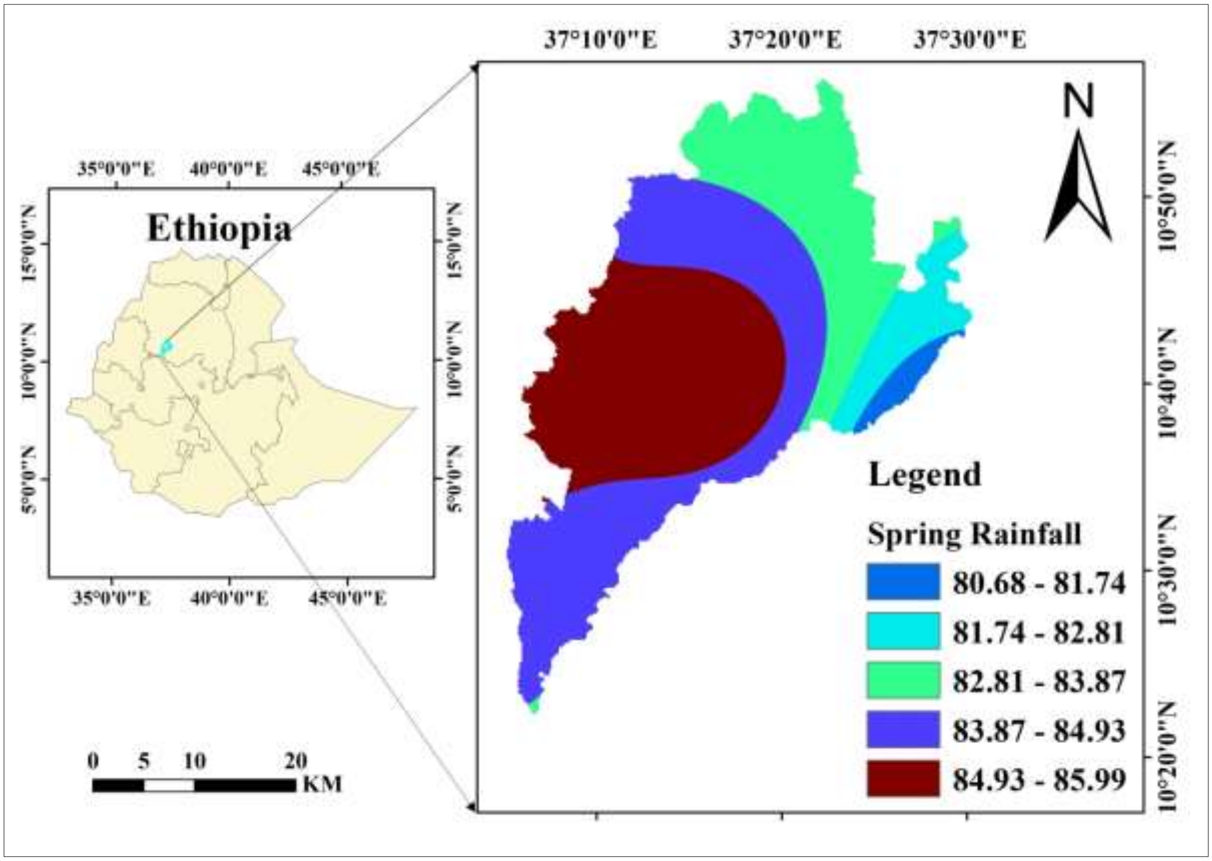
Table 4.1 and Figure 4.3 showed the long-term spatial variability and trends of mean annual rainfall as well as spring, summer, autumn and winter rainfall. In comparison to the other areas, the upper portion of the district experienced the highest annual rainfall (1790–1890 mm/year). The district received rainfall ranging from 1768 mm to 1790 mm annually in more than 57% of cases. An additional 20% of the region experiences yearly precipitation ranging from 1790 to 1812 mm. Furthermore, a sizeable percentage of the district (13%) receives rainfall between 1746 and 1768 mm per year. The smallest amount of rainfall in the area, which ranges from 1702 to 1746 mm annually, falls on the remaining 10% of the district. The distribution of rainfall in space varies seasonally as well. For example, during the winter season (the dry season), the northeastern part of the district receives 8.35 to 8.57 mm (5%) of rainfall on a seasonal basis; this is the driest season in the district. The northeastern part also receives 8.57 to 8.71 mm (10%) of rainfall per season, the north and northwest receives 8.71 to 8.82 mm (20%) of rainfall per season, and the rest of the district receives 8.82 to 8.9 mm (25%) of rainfall the southwest section of the area receives 8.9 to 8.99 mm (40%) of rainfall every season, compared to the southeast and south.

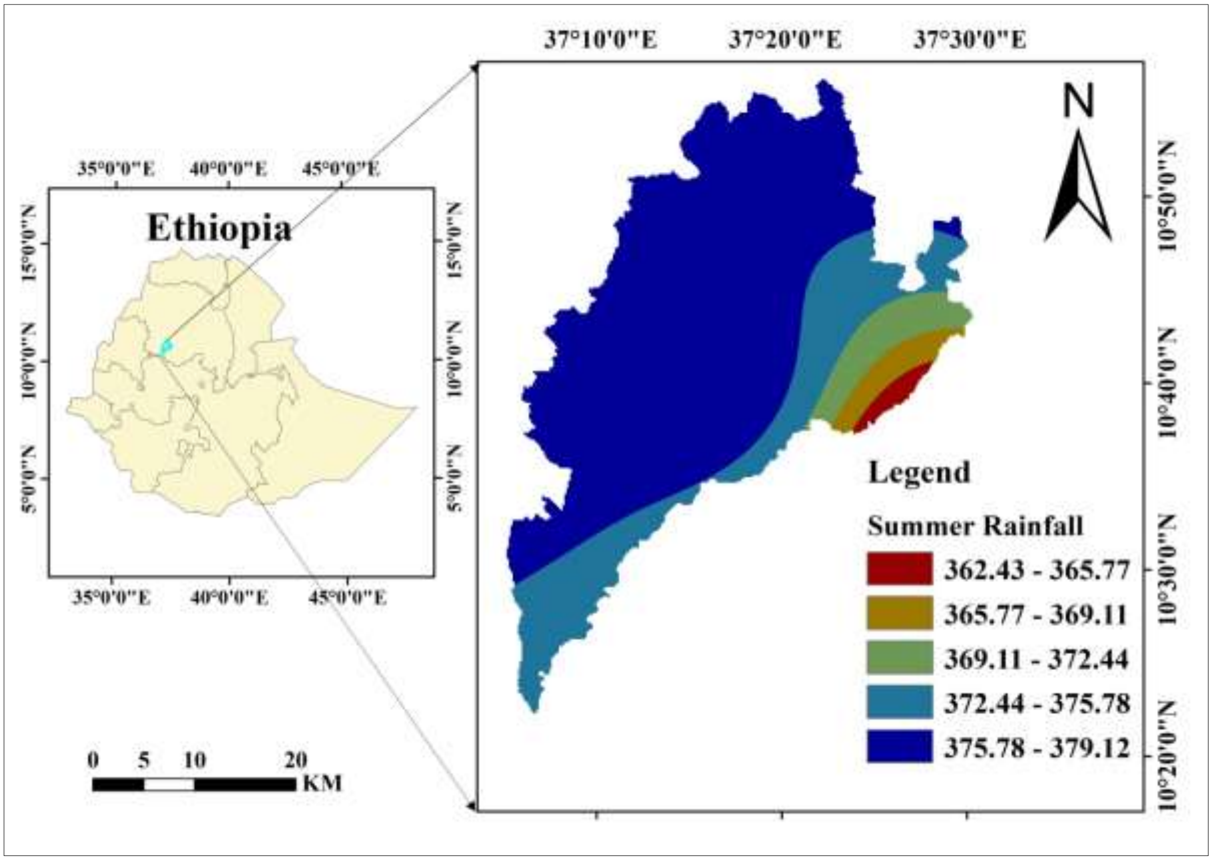
The district experiences varying amounts of rainfall during the spring season, which is the small rainy season. Seasonally, the northeastern part of the district receives 5% of the rainfall, while the north and northwest parts receive 10%, 82.81 to 83.87 mm, and the north and northwest parts receive 20%. Additionally, the south and central parts receive 25% of the rainfall, and the south, central, and southeast parts receive 40% of the rainfall. The district experiences varying amounts of rainfall during the spring season, which is the small rainy season. Seasonally, the northeastern part of the district receives 5% of the rainfall, while the north and northwest parts receive 10%, 82.81 to 83.87 mm, and the north and northwest parts receive 20%. Additionally, the south and central parts receive 25% of the rainfall, and the south, central, and southeast parts receive 40% of the rainfall. According to this, the district is nearly completely covered by the 375.78mm to 379.12mm (80%) of rainfall that falls throughout the summer, the major rainy season. The district's summer rainfall is distributed as follows: the south and southwest receive 372.44 to 375.78 mm (25%) of the total rainfall, the western part receives 369.11 to 372.44 mm (20%) of the total rainfall per season, the western part receives 365.77 to 369.11 mm (10%) of the total rainfall, and the southwestern part receives 362.43 to 365.77 mm (5%) of the total rainfall in each of the district's three agro-ecological zones.

Autumn is the district's small rainy season. Seasonally, the district receives between 124.66 and 126.53 mm of rainfall in the north and northwest tip; from the northwestern tip to the northeastern part of the district, between 126.53 and 128.39 mm of rainfall; from the northwestern tip to the northeastern part of the district, between 128.39 and 130.26 mm of rainfall in the north and northwest part of the district per season; from the southern tip and western part of the district, 130.26 to 132.13 mm of rainfall received; from the central and southwestern part of the district, between 132.31 and 133.99 mm of rainfall received per season (Gebrehiwot *et al.*, 2011; Ayalew *et al.*, 2012; UNFCCC, 2015b; Alemayehu, 2022) all reported findings that were similar.

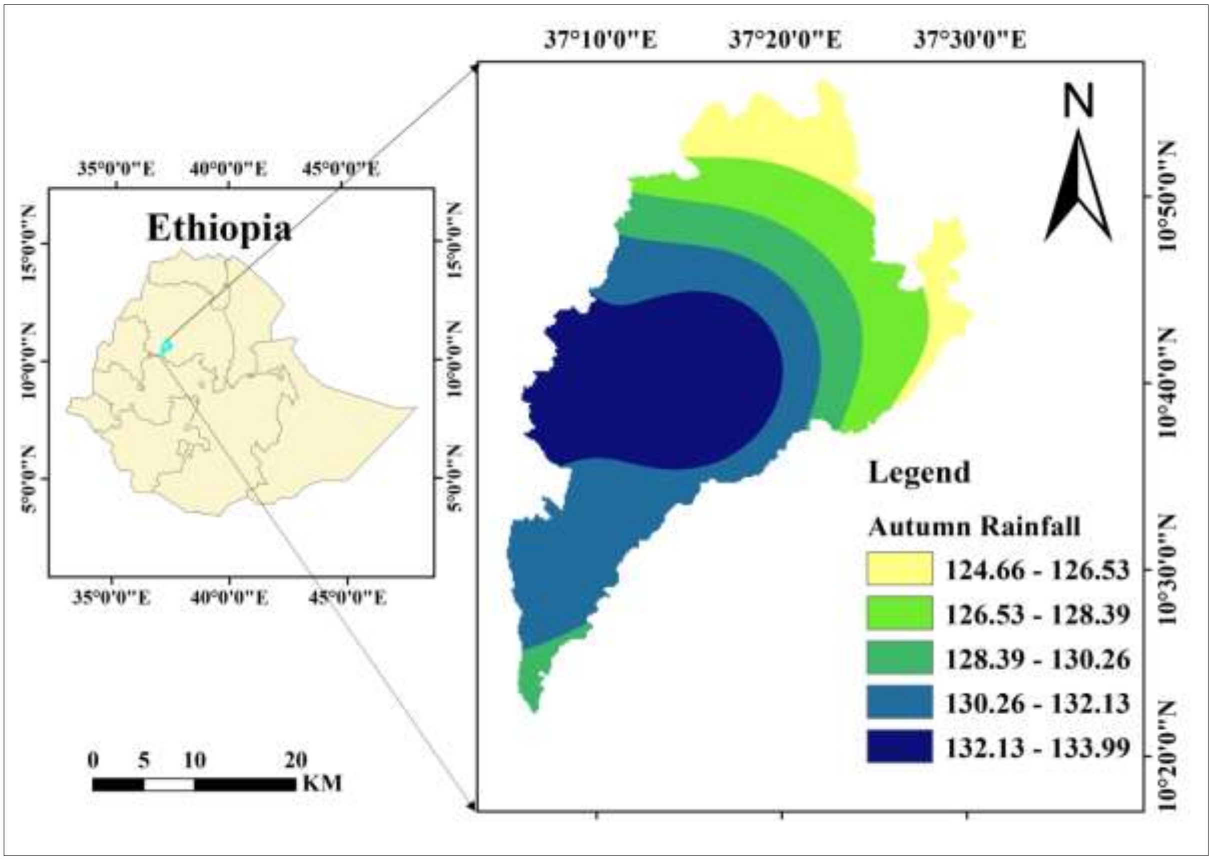


Ethiopia
35°0'0"E
40°0'0"E
45°0'0"E
15°0'0"N
10°0'0"N
5°0'0"N
0 5 10 20
KM
37°10'0"E
37°20'0"E
37°30'0"E
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Winter Rainfall
8.35 - 8.48
8.48 - 8.61
8.61 - 8.74
8.74 - 8.87
8.87 - 8.99


35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
0 5 10 20
KM
37°10'0"E
37°20'0"E
37°30'0"E
N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
Legend
Spring Rainfall
80.68 - 81.74
81.74 - 82.81
82.81 - 83.87
83.87 - 84.93
84.93 - 85.99



37°10'0"E
37°20'0"E
37°30'0"E
35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
Legend
Summer Rainfall
362.43 - 365.77
365.77 - 369.11
369.11 - 372.44
372.44 - 375.78
375.78 - 379.12
0 5 10 20
KM


37°10'0"E
37°20'0"E
37°30'0"E
35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Autumn Rainfall
124.66 - 126.53
126.53 - 128.39
128.39 - 130.26
130.26 - 132.13
132.13 - 133.99
0 5 10 20
KM

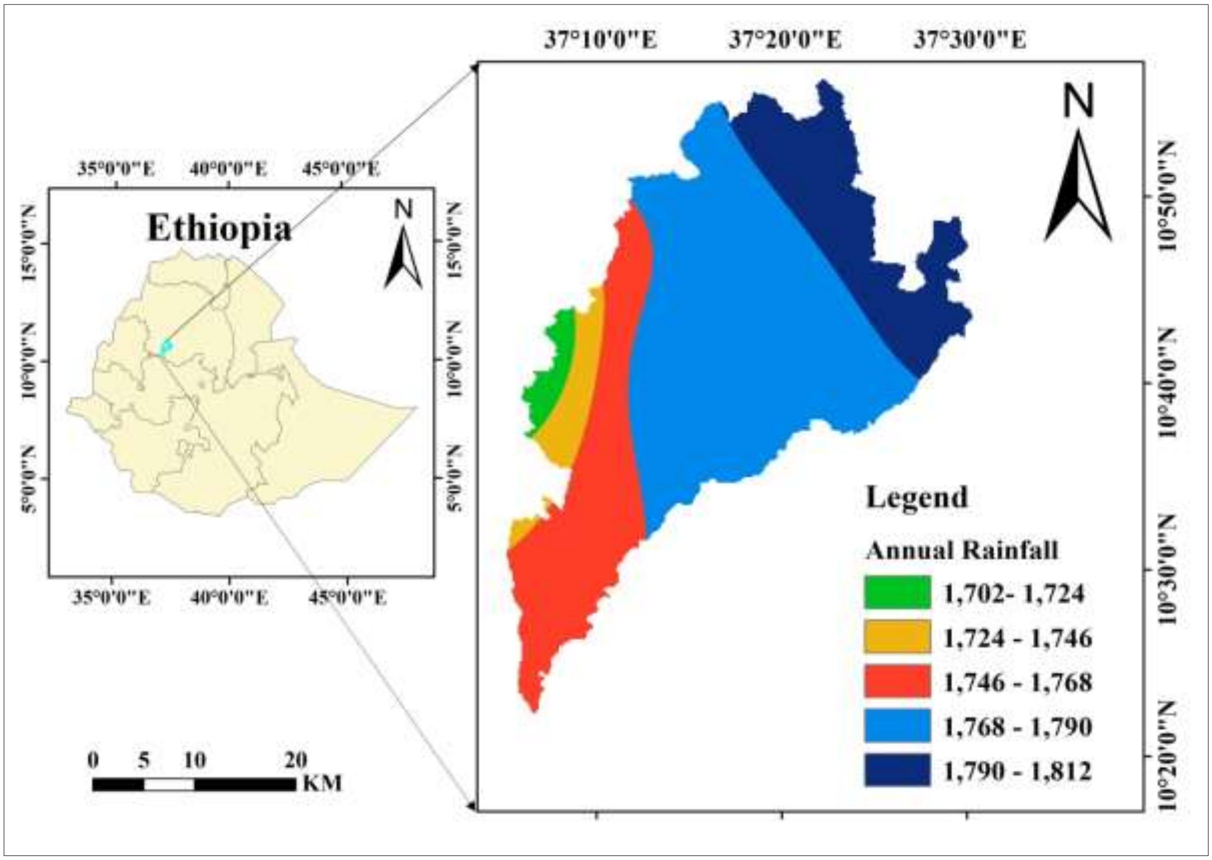


Figure 4. 3 Spatial trends of winter, spring, summer, autumn and annual rainfall (1981-2022)

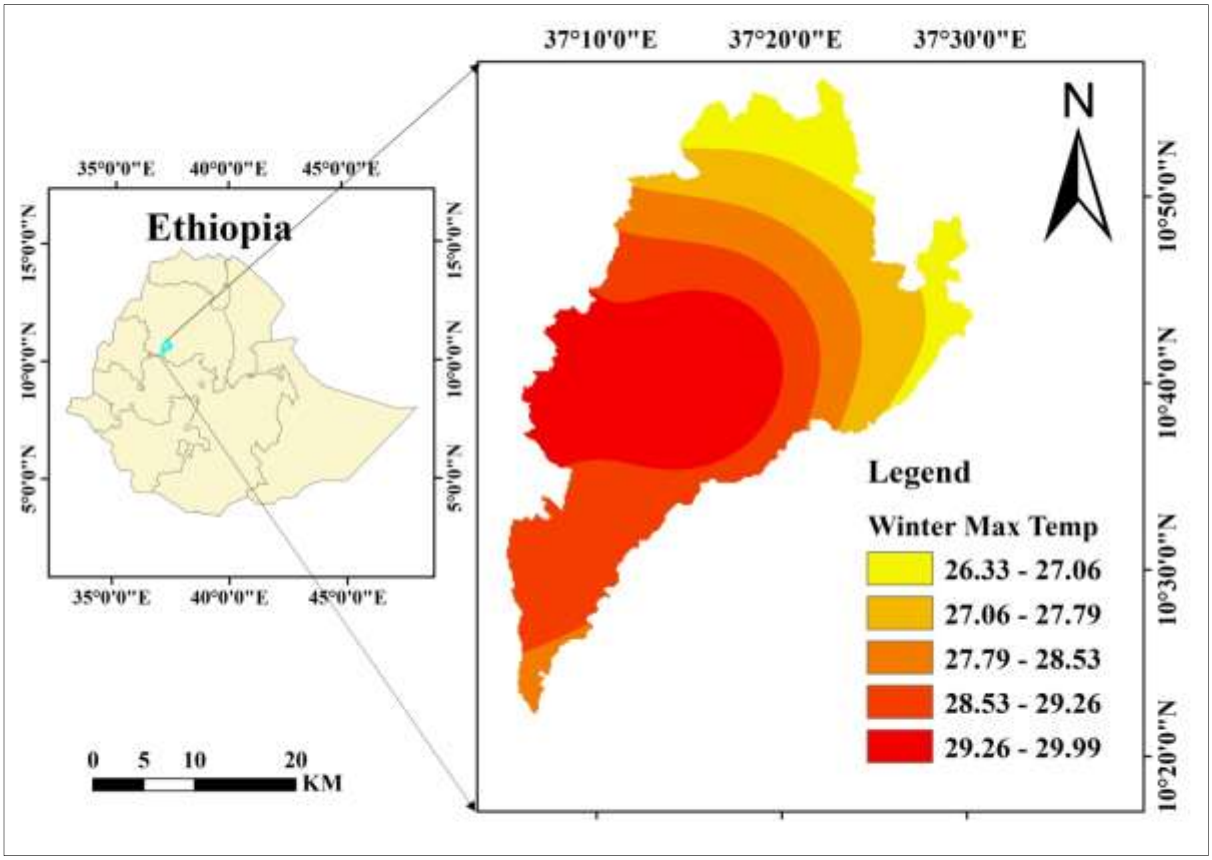
4.4.1 Spatial variability and trend of temperature

Table 4.2 and Figure 4.4 show the long-term spatial variability and trends of the mean annual temperature as well as the temperatures in the spring, summer, autumn and winter. The annual spatial temperature distribution was as follows: the northeastern part of the district receives temperatures between 22.49^{0}C and 25.44^{0}C (5%), the northeastern part receives temperatures between 25.44^{0}C and 27.34^{0}C (10%), the north and northwest receives temperatures between 27.34^{0}C and 28.9^{0}C (20%), the rest of the district receives temperatures between 28.9^{0}C and 30.32^{0}C (25%) and the southwest receives temperatures between 30.32^{0}C and 31.9^{0}C (40%).

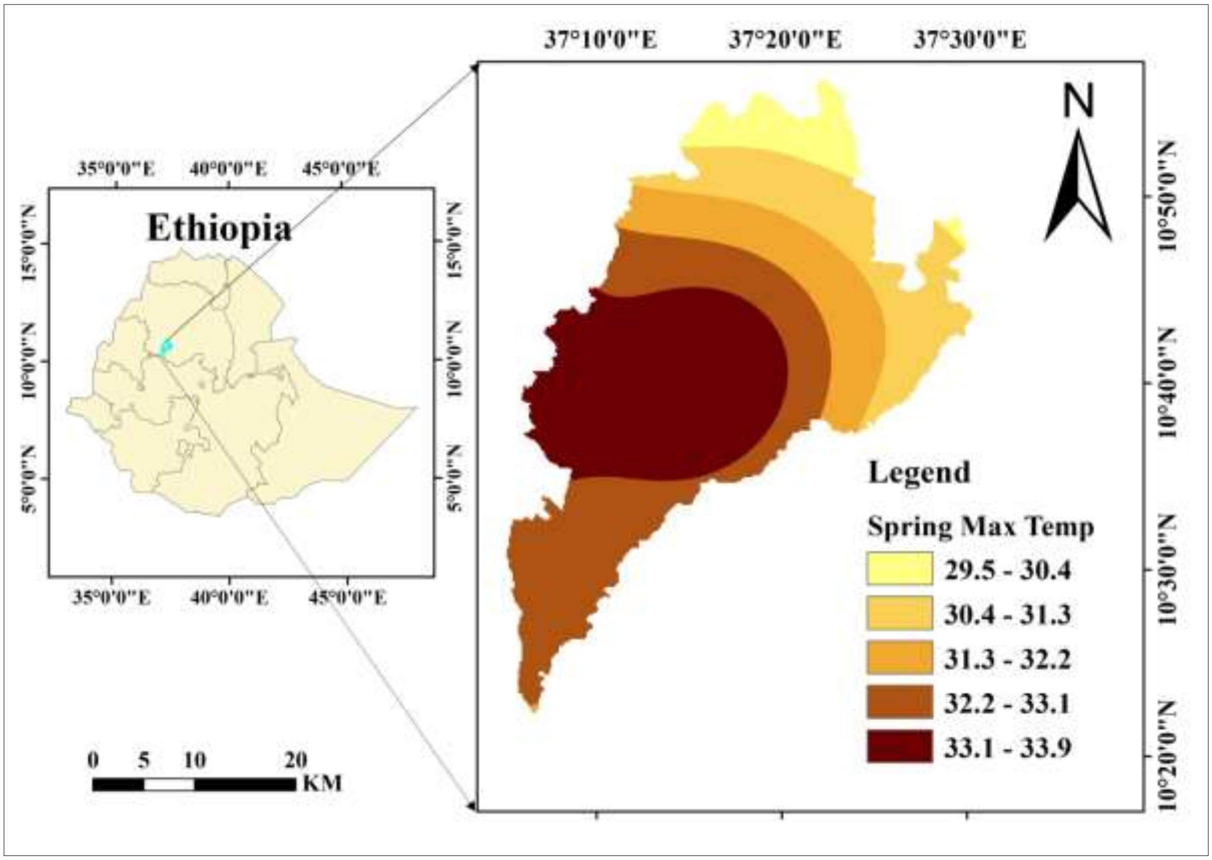
Seasonal variations in the spatial distribution of temperature also occur. Winter season, the maximum temperature experienced seasonally in the northeastern section of the area was 27.06^{0}C to 27.79^{0}C (10%), while the winter season temperature ranges from 26.33^{0}C to 27.06^{0}C

(5%). Additionally, the maximum temperature received by the northeastern portion of the district is between 27.79^{0}C and 28.53^{0}C (20%), while the north and northwest portion of the district receives maximum temperatures between 28.53^{0}C and 29.26^{0}C (25%) and the rest of the central, south, and southeast portion receives maximum temperatures between 29.26^{0}C and 29.99^{0}C (40%). The spring season's maximum temperature, as shown in Figure 4.4, varies in space from 29.5^{0}C to 30.4^{0}C (5%), indicating a seasonally significant increase in the maximum temperature received in the northeastern part of the district; additionally, the northeastern part of the district receives maximum temperatures between 30.4^{0}C and 31.3^{0}C (10%), 31.3^{0}C and 32.2^{0}C (20%), 32.32^{0}C and 33.1^{0}C (25%), and the rest of the central, south, and southeast part of the district receives maximum temperatures between 33.1^{0}C and 33.9^{0}C (40%), and 33.1^{0}C and 33.9^{0}C (45%) of the maximum temperature received in the southwest part of the district.

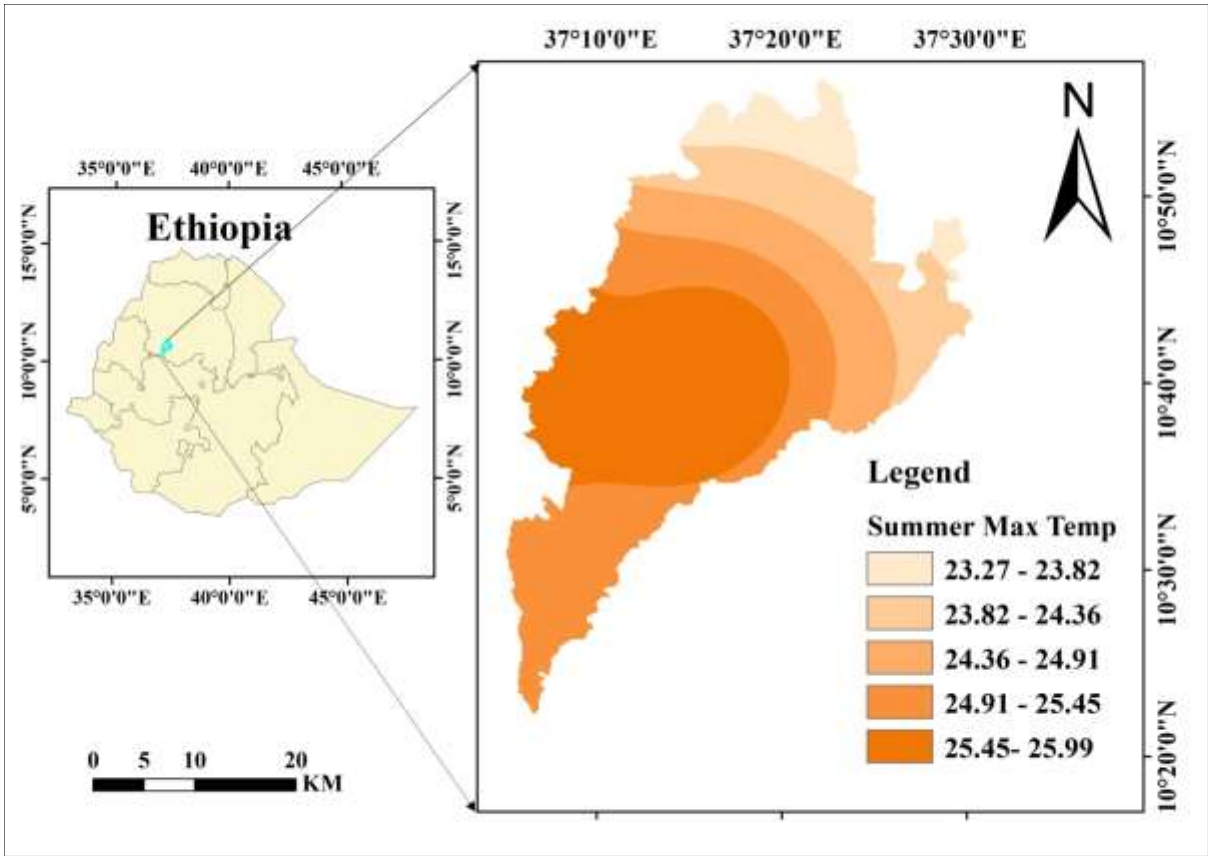
The highest temperature in the summer season ranges from 23.27^{0}C to 23.82^{0}C (5%). Seasonally, the northeastern region of the area experiences high temperatures between 23.82^{0}C and 24.36^{0}C (10%). The northeastern region of the district experiences maximum temperatures ranging from 24.36^{0}C to 24.91^{0}C (20%) depending on the season. maximum temperature received by the district's northwest and northwestern regions is between 24.91^{0}C and 25.45^{0}C (25%) of the maximum temperature received by the rest of the district's central, south, and southeast regions, and between 25.45^{0}C and 25.99^{0}C (40%) of the maximum temperature received by the southwest region. The highest temperature was in the autumn ranges from 22.27^{0}C to 22.82^{0}C (5%). Seasonally, the northeastern region of the area experiences high temperatures between 22.82^{0}C and 23.36^{0}C (10%). The Northeastern Part District experienced a maximum temperature of 23.36^{0}C to 23.91^{0}C (20%) per season. maximum temperature received by the district's north and northwest, which ranges from 23.91^{0}C to 24.45^{0}C (25%) of the maximum temperature received by the rest of the district's central, south, and southeast, and which ranges from 24.45^{0}C to 24.99^{0}C (40%) of the maximum temperature received by the district's south west. The findings aligned with the research conducted by (Teyso *et al.*, 2016; Suryabhagavan, 2017; Asfaw *et al.*, 2018).



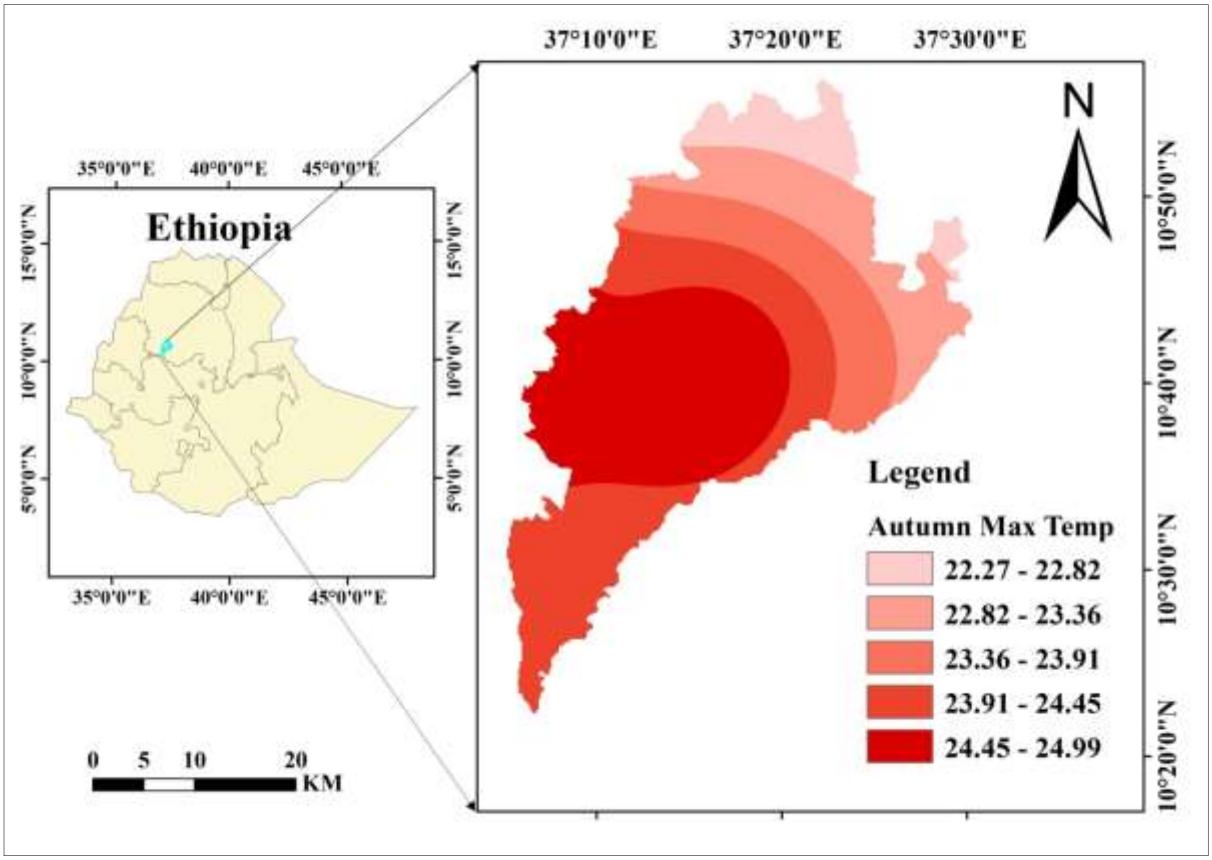
37°10'0"E
37°20'0"E
37°30'0"E
35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Winter Max Temp
26.33 - 27.06
27.06 - 27.79
27.79 - 28.53
28.53 - 29.26
29.26 - 29.99
0 5 10 20
KM



Ethiopia
35°0'0"E
40°0'0"E
45°0'0"E
15°0'0"N
10°0'0"N
5°0'0"N
0 5 10 20
KM
37°10'0"E
37°20'0"E
37°30'0"E
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Spring Max Temp
29.5 - 30.4
30.4 - 31.3
31.3 - 32.2
32.2 - 33.1
33.1 - 33.9



37°10'0"E
37°20'0"E
37°30'0"E
35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Summer Max Temp
23.27 - 23.82
23.82 - 24.36
24.36 - 24.91
24.91 - 25.45
25.45- 25.99
0 5 10 20
KM



37°10'0"E
37°20'0"E
37°30'0"E
35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Autumn Max Temp
22.27 - 22.82
22.82 - 23.36
23.36 - 23.91
23.91 - 24.45
24.45 - 24.99
0
5
10
20
KM

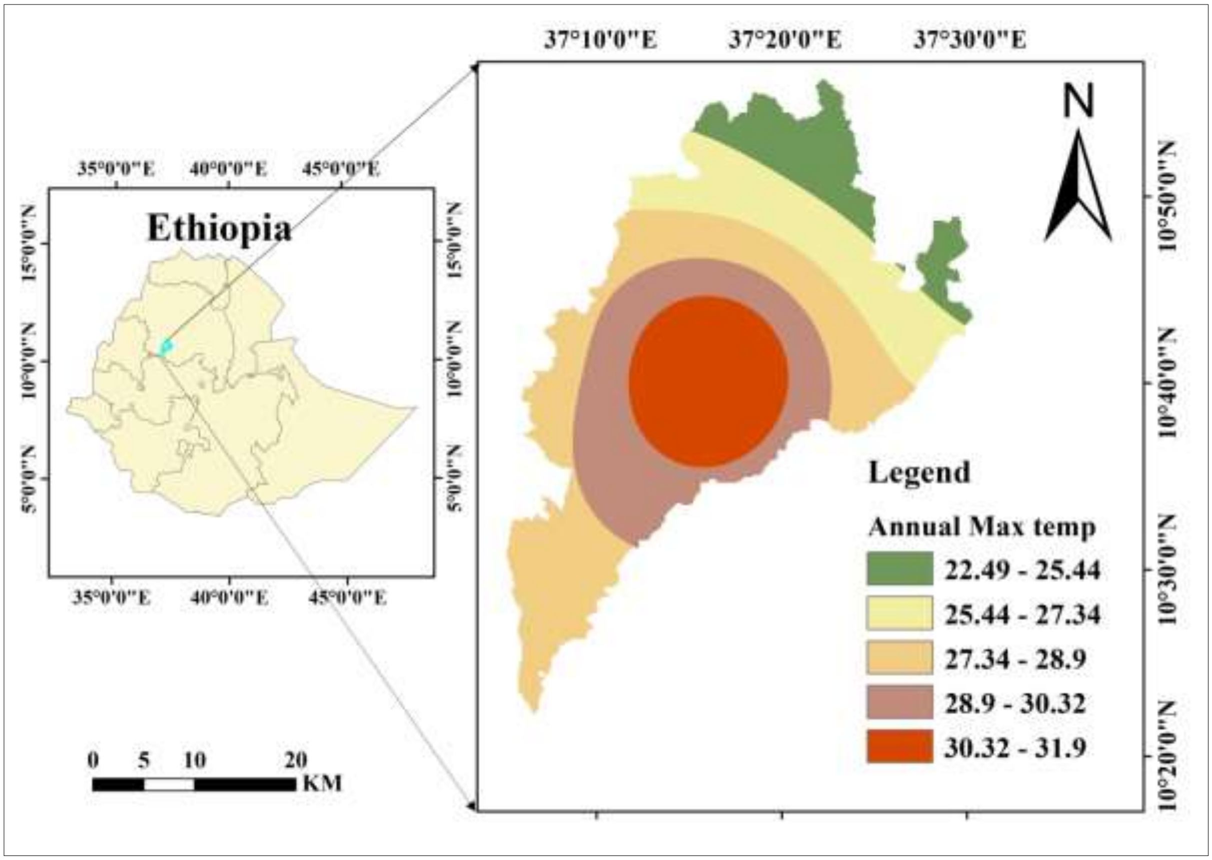
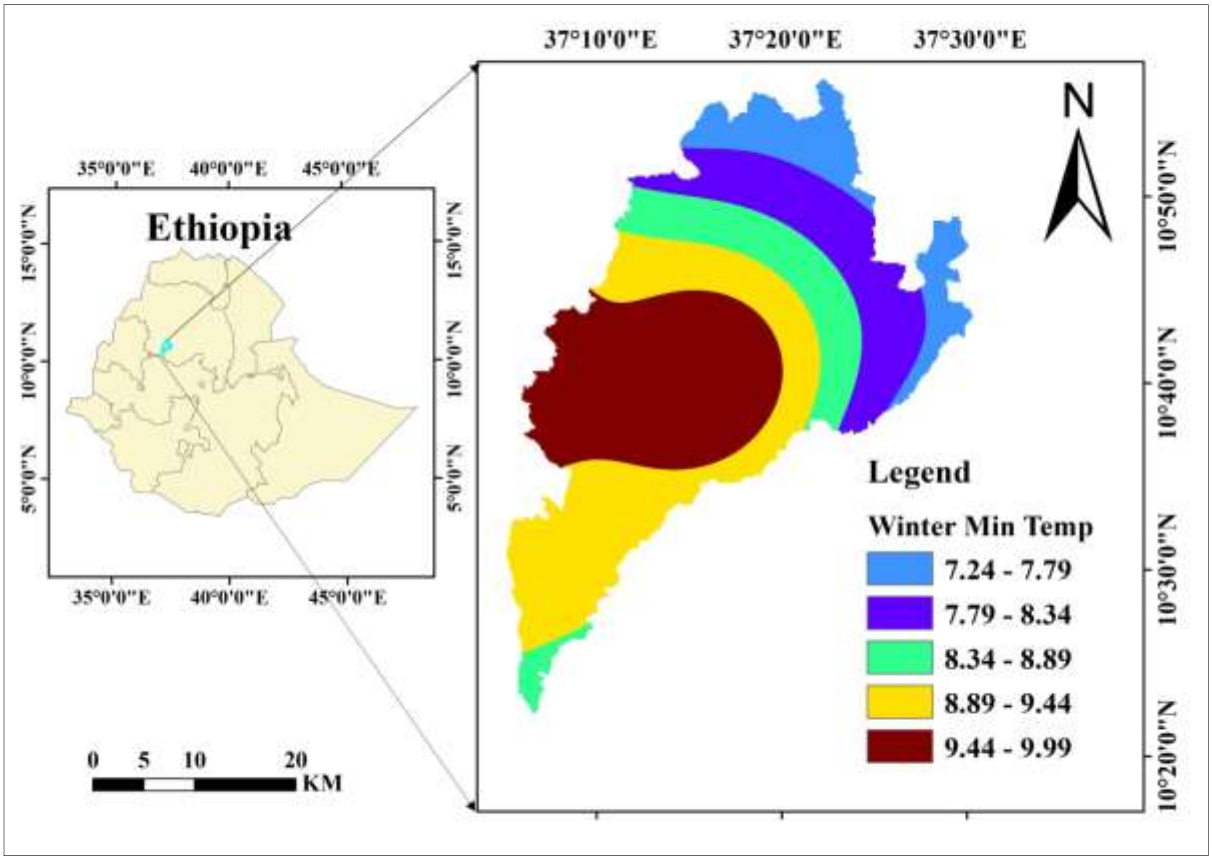


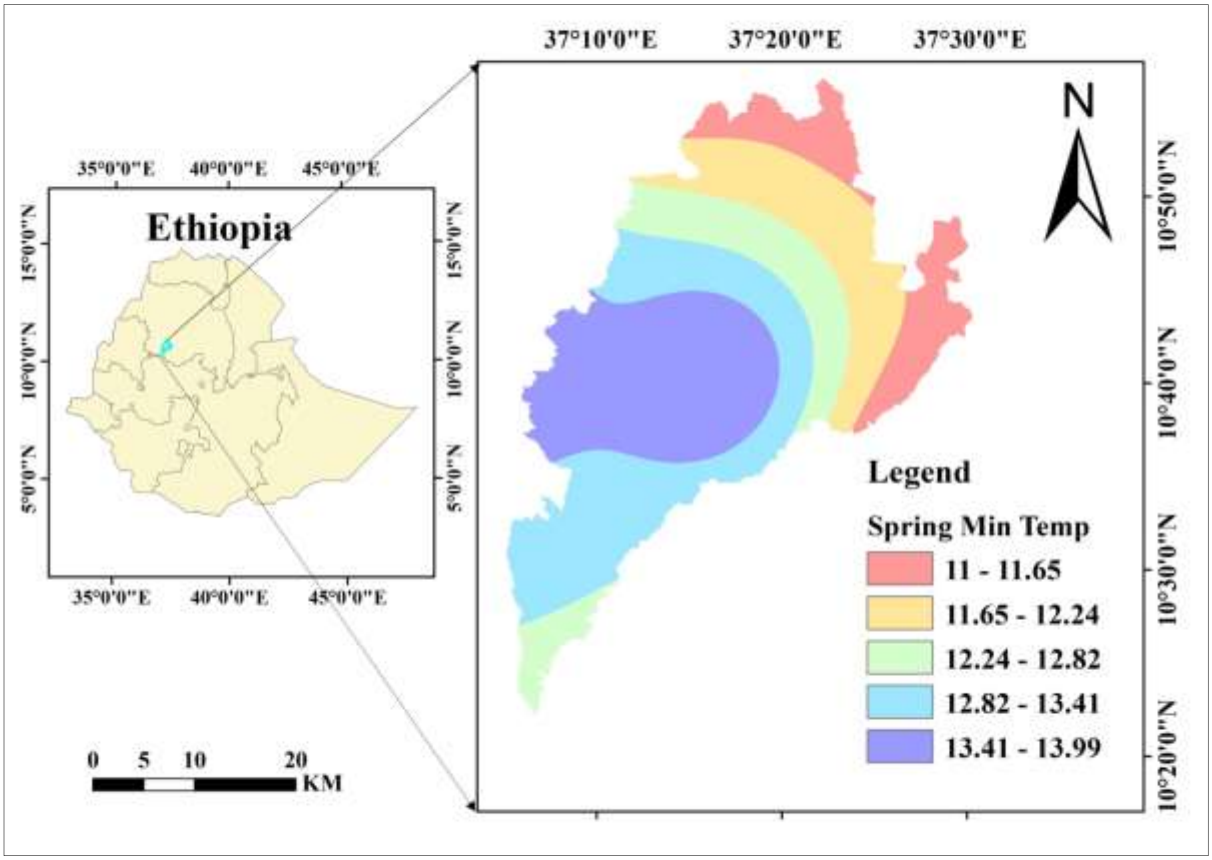
Figure 4. 4 Spatial trends of maximum temperature for seasons and annual from (1981-2022)

The northeastern region of the district receives an annual minimum temperature distribution of 4.6^{0}C to 6^{0}C (5%), while the southeast receives an annual minimum temperature distribution of 6^{0}C to 6.8^{0}C (10%). The northern region of the district likewise experiences a minimum temperature of 6.8^{0}C to 7.5^{0}C (20%) annually. Minimum temperatures are received in the south and southwest of the district annually, in the outer shell of the central district annually between 7.5^{0}C and 8.2^{0}C (25%) and in the central section of the district annually between 8.2^{0}C and 8.9^{0}C (40%). In the winter which is the coolest season, the minimum temperature ranges from 7.24^{0}C to 7.79^{0}C (5%). The northeastern region of the district experiences a seasonal minimum temperature range of 7.79^{0}C to 8.34^{0}C (10%). Additionally, the northeastern portion of the district receives temperature readings from 8.34^{0}C to 8.89^{0}C (20%), the north and northwest portion of the district receives 8.89^{0}C to 9.44^{0}C (25%) of minimum temperature readings, and the rest of the central, south, and southeast portion of the district records 9.44^{0}C to 9.99^{0}C (40%) of minimum temperature readings. Based on the data presented in Figure 6, it can be observed that the minimum temperature in the spring varies in space from 11^0C to 11.65^0C (5%). This indicates a seasonally increasing trend in minimum temperature received by the northeastern part of the district, from 11.65^0C to 12.24^0C (10%), and from 12.24^0C to 12.82^0C (20%) in the north and northwest regions of the district each season, with the remaining centre, south, and southeast regions receiving 12.82^0C to 13.41^0C (25%) of the minimum temperature and the southwest region receiving 13.41^0C to 13.99^0C (40%) of the minimum temperature.

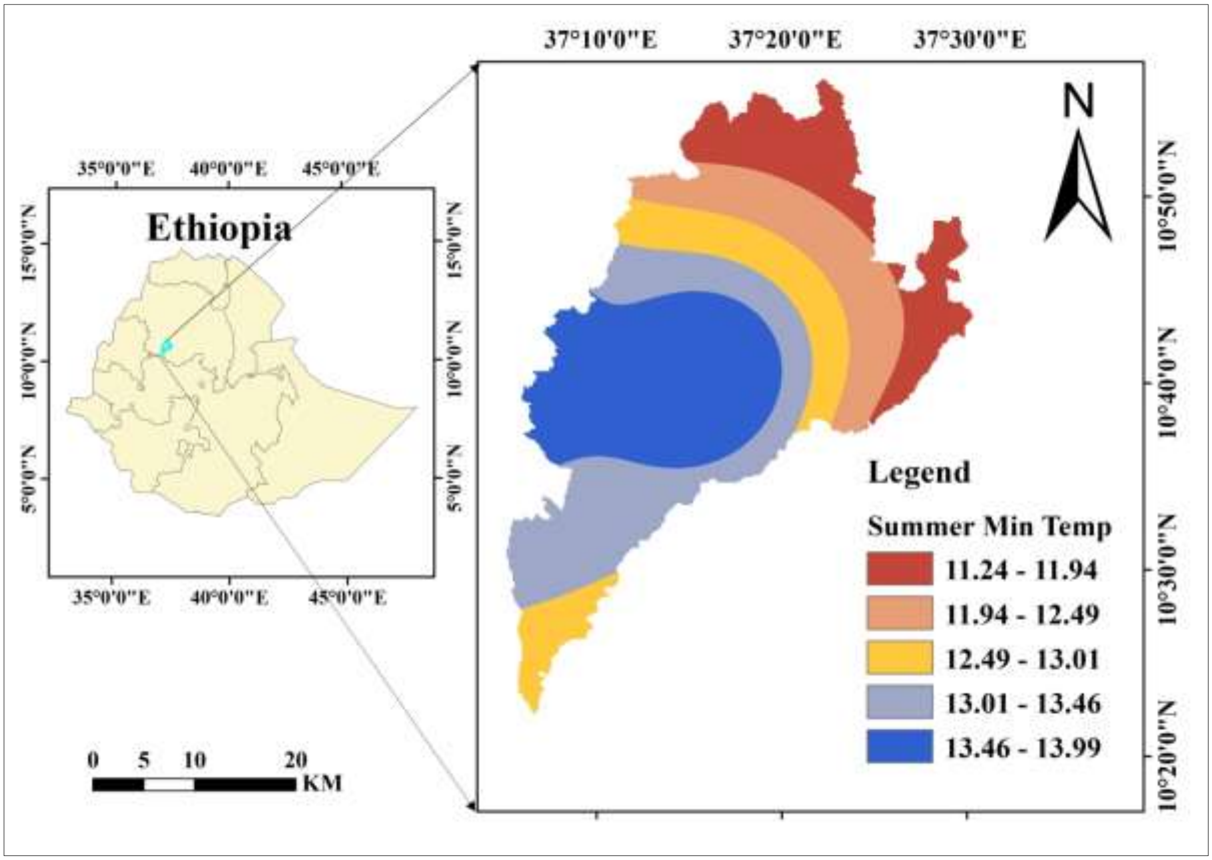
The minimum temperature in the summer ranges from 11.24^0C to 11.94^0C (5%). Seasonally, the northeastern region of the district experiences minimum temperatures between 11.94^0C and 12.49^0C (10%). The northeastern region of the district experiences minimum temperatures ranging from 12.49^0C to 13.01^0C (20%) depending on the season. Minimum temperatures are received in the north and northwestern parts of the district per season; the rest of the central, south, and southeast parts of the district receive minimum temperatures between 13.01^0C and 13.46^0C (25%) and the south west part of the district receives minimum temperatures between 13.46^0C and 13.99^0C (40%) per season. The minimum temperature throughout the autumn season ranges from 7.67^0C to 8.45^0C (5%). Seasonally, the north-east portion of the district experiences minimum temperatures between 8.45^0C and 9^0C (10%), and throughout the district season, minimum temperatures between 9^0C and 9.6^0C (20%). minimum temperature received by the district's north and northwest each season; 9.6^0C to 10^0C (or 25%) of minimum temperature received by the remaining central, south, and southeast regions each season; and 10^0C to 10.7^0C (or 40%) of minimum temperature received by the district's southeast region Figure 4.5. In the eastern and northeastern regions of the country, the minimum temperature showed a combination of significant declining and non-significant trends, yielding the same result across different regions Figure 4.5.

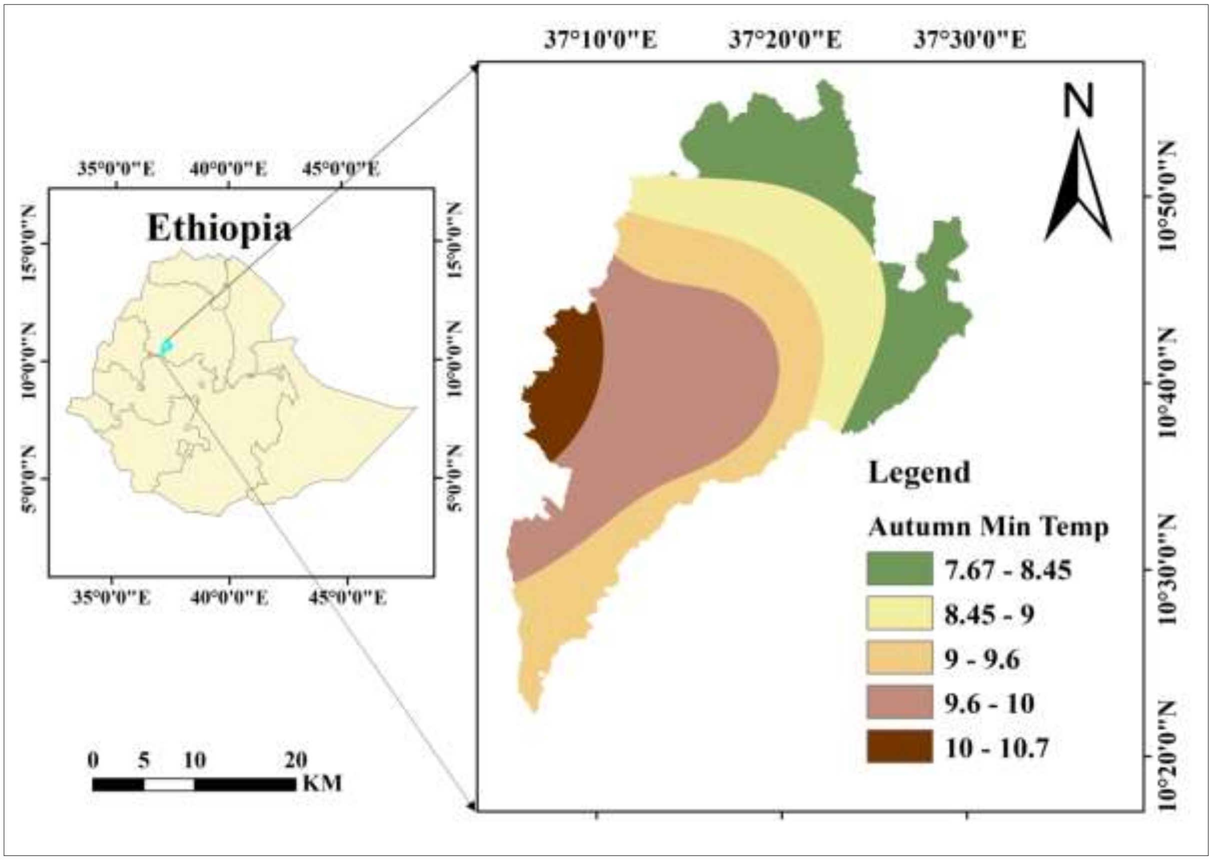


37°10'0"E
37°20'0"E
37°30'0"E
35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Winter Min Temp
7.24 - 7.79
7.79 - 8.34
8.34 - 8.89
8.89 - 9.44
9.44 - 9.99
0 5 10 20
KM



37°10'0"E
37°20'0"E
37°30'0"E
35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Spring Min Temp
11 - 11.65
11.65 - 12.24
12.24 - 12.82
12.82 - 13.41
13.41 - 13.99
0 5 10 20
KM


Ethiopia
35°0'0"E
40°0'0"E
45°0'0"E
15°0'0"N
10°0'0"N
5°0'0"N
0 5 10 20
KM
37°10'0"E
37°20'0"E
37°30'0"E
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
N
Legend
Summer Min Temp
11.24 - 11.94
11.94 - 12.49
12.49 - 13.01
13.01 - 13.46
13.46 - 13.99


35°0'0"E
40°0'0"E
45°0'0"E
Ethiopia
15°0'0"N
10°0'0"N
5°0'0"N
0 5 10 20
KM
37°10'0"E
37°20'0"E
37°30'0"E
N
10°50'0"N
10°40'0"N
10°30'0"N
10°20'0"N
Legend
Autumn Min Temp
7.67 - 8.45
8.45 - 9
9 - 9.6
9.6 - 10
10 - 10.7

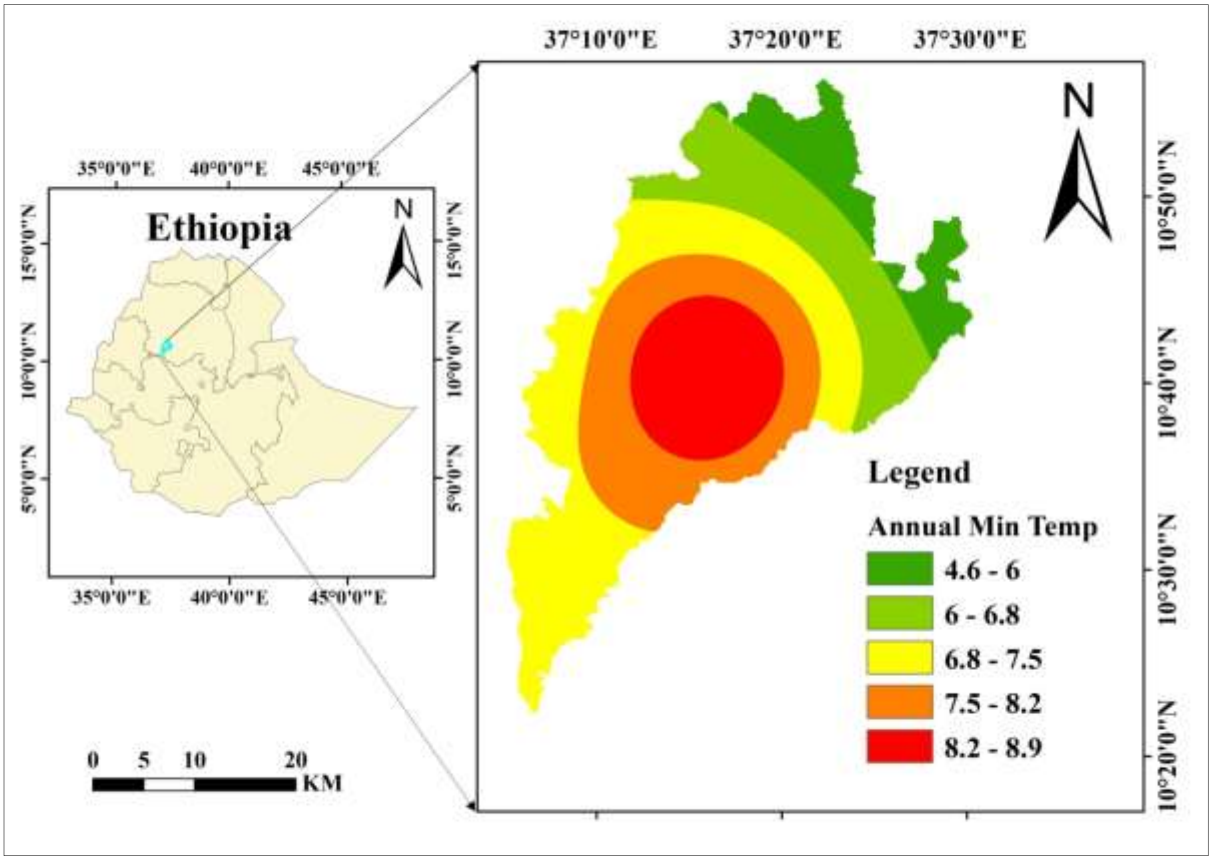


Figure 4. 5 Spatial trends of minimum temperature for seasons and annual from (1981-2022)

4.5 Discussion

Rainfall distribution and erratic rainfall distribution (49.5%), the statistical analysis reveals that there is a range of variability in spatiotemporal rainfall and temperature within the district (Mekonen *et al.,* 2020). This variability spans from moderate to high levels, both seasonally and annually. As an example, rainfall exhibited high variability (CV > 36.4) in the district during the autumn, winter and spring seasons, while it showed moderate variability during the annual and summer seasons (CV 21.3 to 23.1) (MinistryofWater, 2016) also found there was a greater variation noted during the autumn and winter seasons in comparision to the yearly and summer period (Sharma *et al.*, 2024). Further research findings indicated that there was greater rainfall variability noted throughout the autumn, spring and winter period comparision to the summer period in the northeastrn highlands,north eastrn ethiopia,westrn ethiopia and northwest parts of Ethiopia (MinistryofWater, 2016; Alemayehu *et al.*, 2020a; Bahiru *et al.,* 2020; Wassie *et al.*, 2022). The mankendall trend test indicated that seasonal (winter, summer, autumn) annual rainfall exhibited a slight decreasing trend, while a significant declining trend was observed for spring season rainfall (Woldeamlak Bewket *et al.*, 2007; Mekonen *et al.*, 2020; Rawashdeh *et al.*, 2024). In addition this result also has similarity with (MinistryofWater, 2016) which winter, autumn, and summer, along with the entire year, also provided evidence that, apart from the autumn period (2.41 mm per season), the remaing periods exhibited declining pattern within the research area.

The study area, as indicated by the findings, rainfall summer period (June, July and Augest) accounted for most of the total yearly rainfall. Outlined table 1, June contributed 12.8%, July contributed 14.7%, and August contributed 21.05% of the overall rainfall (Feke *et al.*, 2021). The period from 1981 to 2022 witnessed the minimum mean rainfall during the month of December, January and feburuary the dry or winter season the majourity part of Ethiopia encompassing the current research area (Enyew *et al.*, 2024). This result strongly inlined with the study done by Feke *et al.* (2021) at Horro Guduru Wollega Zone of Oromia National Regional State.

As shown in Table 2, the yearly PCI during the period from 1981 and 2022 was primarily defined by erratic rainfall distribution (55.4%) of the observation years. Summer season belongs to erratic rainfall distribution (17.4 %) also spring and autumn season shows irregular and (42.3%) of the seasons respectively. Similar results reported by (Feke *et al.*, 2021; Alemayehu *et al.*, 2022; Wassie *et al.*, 2022) from Horro Guduru Wollega Zone of Oromia National Regional State, Suha watershed, Upper Blue Nile Basin, Northwest Ethiopia, and western Ethiopia.

4.5.1 Potential influence of rainfall and temperature variability

The observed spatial and temporal variations in rainfall and temperature could have significant impacts on farming methods and crop yields among smallholder farmers. Adequate and timely rainfall in terms of amount and duration during the winter, spring, summer, autumn, and annual seasons is crucial for agricultural activities. However, the inconsistency and variability of rainfall during spring (March, April, May) and Summer (June, July, August) seasons depressing agricultural practices and productions over the three agro-ecological zones. However, the delayed onset of rainfall in June and the early cessation of rainfall in September have been affecting farmers' ability to plant early and on time, as well as hindering the active growth and maturation of various crops. This ultimately affected farming output by introducing instability into the planting schedule. For instance, authors such as (Dinku, 2010; Asfaw *et al.*, 2018) it was observed that in fluctuation in the quantity and duration of precipitation throughout the spring and summer seasons resulted in losses in agriculture and cattle production, pushing families into persistent food insecurity. Regassa *et al.* (2010) further suggested that spring rainfall may affect the production of long-cycle crops, leading to severe consequences for agricultural output. Similarly, (Bewket, 2009) further predicted that fluctuating rainfall costs 38% of the nation's possible growth rate and rise poverty level by 25%, added that sever rainfall fluctuation is a key driver of fluctuations in cereal growth, leaving subsistence cultivators highly vulnerable to hunger crisis. Additionally, rising pattern in yearly and periodical temperatures during research time could exert significant pressure on the crop production process for smallholder farmers.

The incremental trend yearly and period temperatures when the research time could have a profound effect crop production procedures of family's cultivators. For example, (Daninga *et al.*, 2015) stated that warming will amplify the impact of droughts, which reduces the soil's moisture levels impacting the productivity of agricultural land. Gebreegziabher *et al.* (2020) was also projected that rising annual and seasonal temperatures would reduce crop yields per hectare.

In general, the possible effect of climate fluctuation on agricultural output primarily driven by its sensitivity to changes in pricipitation and temperature. This is because agriculture output has a narrow range of optimal and tolerable rainfall and temperature conditions for healthy growt (Gebreegziabher *et al.*, 2020). In summary, discussions highlight that temperature and precipitation fluctuation significantly reduces agricultural output and undermines the overall success of the agricultural sector. During periods of severe climate variability, these impacts can escalate to complete crop failure, resulting in famine and the loss both human and animal lives (Mekonen *et al.*, 2020).

4.6 Conclusion

The study identified both temporal and geographical fluctuations in rainfall and temperature in the Jabitehinan district. There were seasonal differences in rainfall trends, with minor increases observed across all seasons and the annual average. Temperature exhibited a consistent increasing trend across all seasons and in annual averages. These findings suggest that the Jabitehinan district is experiencing climate variability, which could impact agriculture, water resources, and ecosystems in this predominantly agrarian region. Rising temperatures may exacerbate evapotranspiration and reduce water availability, while changing rainfall patterns could affect crop productivity. Rainfall distribution showed variability across the district, with higher rainfall in the upper highlands and less in the middle and lower regions. The highest rainfall concentrations were limited to specific parts of the district, highlighting localized disparities. Spatial variations in rainfall could lead to unequal access to water resources, affecting both farming practices and water management. Areas with less rainfall might face greater water stress, requiring adaptive interventions. The decadal increase in temperature across all seasons indicates a long-term warming trend. Long-term warming may intensify climate challenges, such as reduced crop yields, shifts in growing seasons, and increased risks of heat stress for humans and livestock.

This study faced limited temporal coverage of data, if the dataset used for analysis only spans four decades, it may not capture long-term climate variability or extreme events comprehensively. Regional Specificity was another shortcoming of this study; the findings are specific to the Jabitehinan district and may not generalize to other regions of Ethiopia, even those in similar highland environments. The researchers strongly recommended that other scholars include longer datasets and integrate global climate models to validate and predict future trends.

Chapter Five

Perceptions and Determinants of Climate Change Awareness among Farmers across Agro-Ecological Zones in Jabitehinan District, Northwestern Ethiopia[3]

5.1 Introduction

According to the Intergovernmental Panel (IPCC, 2006) climate change is defined as a change in the state of the climate that can be identified by alterations in the mean and/or variability of its properties and that persists for an extended period, typically decades or longer. Perception is viewed as a crucial factor influencing climate action. It is included to enhance the legitimacy of climate policies and the generation of knowledge regarding climate change (Hügel *et al.*, 2020). Incorporating perceptions of climate change can also enhance public and scientific communication about the phenomenon (Mendoza-Poudereux *et al.*, 2021).

According to Maddison (2007), perceiving change and then deciding whether or not to adopt a particular measure is process in climate change adaptation. Whenever they have the opportunity, farmers tend to adopt new variety of measures or technologies in response to the perceived changes of weather conditions. The supports from extension workers, information gained and technologies available to them will highly influence their adaptation and response capacity. For instance, farmers use water conservation techniques whenever the rainfall patterns are changed and amounts of rain are reduced. They tend to plant different crop varieties and use short term crops with adjustment of planting dates. These adjustments are done when they perceive reduction in rainfall and changes in the onset and offset of rainy seasons.

[3]Accepted for Publication and under Production in the journal of *Scientia Agriculturae Bohemica*

The study by Fosu-Mensah *et al.* (2012b) showed that farmers are well aware of climate change, but few seem to actively take steps toward adjusting their farming activities. According to Deressa *et al.* (2011b), majority of farmers were able to recognize that temperatures have increased and there has been a reduction in the volume of rainfall, still few farmers lack the perception of change in climatic condition of their area to take steps to adjust their farming activities. The degree of farmer's perception on climate change also depends on its impact on farmer's livelihood, their social, institutional and economic background. It is different and depends mainly on level of education, livelihood activity, location and age.

In order to get essential information and insight into farmer's adaptation to climate change, looking at their perception on each climate attributes were quite important. Descriptive statistic and Likert scale measurement were used to characterize farmer's perception on changes in long-term temperature, rainfall and other aspects.

To analyze smallholder farmers perception to change in climate, further comparison were made correspondence with climate data recorded in Finoteselam metrological station for 41 years for the period (1981-2022) by fitting a linear trend of annual means of temperature and rainfall. Making this trend in annual average temperature and rainfall a base for comparison, the perception of farmers were analyzed whether it was in line with or opposite to the linear trend fitted from the data. This has been done by asking household heads questions about their opinion on the direction of climate change and using a five level Likert scale measurement on some attributes of climate change. Percentages were used to analyze the proportion of respondent in each level. Farmers who strongly agree and who simply agree were considered perceived the change while others not. Percentages were also used to identify adaptation options used by farmers.

According to the belief of majority of participants in the focus group discussion, today's climate change and its consequences are the results of umbrage of God (Ademe *et al.*, 2020). In addition, they respond that there is a high level of deforestation and old aged trees are being cut for the purpose of timber (Akano *et al.*, 2023). According to their saying, the local government is the primary responsible body for this evil practice. Each year, new seedling will be planted. But because of poor follow up and management, almost all seedlings ceased to survive. The other practice that aggravates climate change is the production of charcoal by cutting trees in the area (Alam *et al.*, 2017).

The farmers were asked about their perception to the condition of climate in their district. To do this, the two known climate attributes; the condition of temperature and rainfall have been used. Temperature and rainfall parameters in annual average temperature and annual average rainfall were used to describe farmer's perception on climate change. For the analysis of perception of farmers to climate change, the trends of climate data recorded at meteorological station have been compared with the view of farmers about the direction of changes in temperature and rainfall. Descriptive statistics measurement was used to provide insights into farmer's perceptions of climate change.

5.2 Data source and Sampling design

In this study, a sample of 361 smallholder households was taken from Jabitehinan district smallholder farmers (Table 5-1). In order to select these respondents a two-stage sampling approach was employed. First, three Kebeles were selected in the district purposively based on agro-ecological zones and the intensity of the impact of the climate change and variability. Second, using systematic sampling method households were selected from each of the three kebeles Zengebal Bedega, Woga Guanesa, and Ergib Kebromeda proportionally. In this case the lists of the households were collected from the kebeles administrator's and development agent officials of each kebeles first. In systematic sampling method by using random numbers to pick up the unit with which to start, an element of randomness is usually introduced. This sampling procedure is useful when sampling frame is available in the form of a list. In such a design the selection process starts by picking some random point in the list and then every nth element is selected until the desired number is secured (Kothari, 2004).

Table 5. 1 sample household data from the three agroecological zones

No	Name of Kebeles	Agro-climatic Zone	House Hold size	Sample size
1	Zengebal Bedega	Temperate-highland	1160	116
2	Woga Guanesa	Sub-tropical	1530	153
3	Ergib Kebromeda	Semi-arid	920	92
			3,610	361

Key informants and FGD participant selection was carried out those kebeles a knowledgeable person who has valuable viewpoints about local observed facts and opinions related to climate variability. Six KI interviewees include experts at regional and district level selected purposively based on their work experience and educational status to give detail information about climate variability and the perception of the community. The recruited participants in FGD integrated male and female households, local community leaders and development agents. There were four FGD groups; One FGD comprised six participants to discuss on the issue of climate change and variability to answer the second objective the perception of the community.

Descriptive statistics were used to characterize farmer's perception on changes in long-term temperature, rainfall and other aspects. To analyze smallholder farmers perception to change in climate, further comparison were made correspondence with climate data recorded in Finote Selam Sub-station for 41 years for the period (1981-2022) by fitting a linear trend of annual means of temperature and rainfall. Making this trend in annual average temperature and rainfall a base for comparison, the perception of farmers would be analyzed whether it was in line with or opposite to the linear trend fitted from Finote Selam Meteorological data. This has been done by asking household heads questions about their opinion on the direction of climate change on some attributes of climate change. Percentages were used to analyze the proportion of respondent in each level. Farmers who strongly agree and who simply agree were considered perceived the change while others not. Chi-square was employed to evaluate the importance of variation on evaluated variables between agro ecology (semi-arid, sub-tropical and temperate highland) at p-value < 0.05.

The **Chi-square (χ^2) formula** depends on the type of test being done, but the general formula is:

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

Where:

- O_i = Observed frequency (actual data)
- E_i = Expected frequency (based on hypothesis or model)
- The summation (Σ) is over all categories or cells.

The word-based approach was utilised to extract themes from the FGD participants' responses and open-ended inquiries, which were subsequently coded for a straightforward count analysis ranking.

Logistic regression model was employed to analyze determinants of farmers' perception of climate change and variability.

Binary Logit Model Formula

$$P(Y = 1|X) = \pi(X) = \frac{e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{11} X_{11}}}{1 + e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{11} X_{11}}}$$

: log-odds form is:

$$\ln\left(\frac{\pi(X)}{1 - \pi(X)}\right) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_{11} X_{11}$$

Table 5. 2 Description of predictor variables

Predictor Variables	Variable type
Age	Continuous
Gender (1=Male 0=Female)	Categorical (Dichotomous)
Education (0=can't read write 1= can read and write)	Categorical (Ordinal)
Farming experience (years)	Continuous
Access to irrigation(1=user 0=non-user)	Categorical (Dichotomous)
Training (1acces to training 0=not get training)	Categorical (Dichotomous)
Formal weather forecasts (1=Access to information 0= Not access to information)	Categorical (Dichotomous)
Indigenous early warning(1=Practiced 0=Not practiced)	Categorical (Dichotomous)
Annual income (per 10,000 Birr)	Continuous
Extension contact(1=has contact 0= not contacted)	Categorical (Dichotomous)
Off-farm activities (1=Yes 0= No)	Categorical (Dichotomous)
Semi-Arid zone (1=Yes 0=No)	Dummy
Sub-humid zone (1=Yes 0=No)	Dummy

A one-way ANOVA followed by Tukey's Post-Hoc test was performed to compare farmer's perception on climate change across the three agro-ecological zones. Statistical significance was set at the $p < 0.05$ level, with distinct letters assigned to the means indicating significant differences. In this analysis, agro-ecological zone was treated as the independent variable, while farmers' perception of climate change was considered the dependent variable. A one-way analysis of variance (ANOVA) was employed to examine whether farmers' perception scores differed significantly across agro-ecological zones.

ANOVA Formula Components

- **Total variation**

$$SST = \sum_{i=1}^{k} \sum_{j=1}^{n_i} (Y_{ij} - \bar{Y}_{..})^2$$

- **Between-group variation**

$$SSB = \sum_{i=1}^{k} n_i (\bar{Y}_{i.} - \bar{Y}_{..})^2$$

- **Within-group variation**

$$SSW = \sum_{i=1}^{k} \sum_{j=1}^{n_i} (Y_{ij} - \bar{Y}_{i.})^2$$

5.3 Results and Discussion

5.3.1 Farmer's perception on climate variability by different agro-climatic zone

This section presents the knowledge, perceptions and understanding of the concept of climate variability by different agro-ecological zone farmers of Jabitehinan District in Amhara region. The findings reveal that despite changes occurring in the environment the concepts of climate and climate variability are understood but perceived differently by different people at varied levels in the community. The majority of the respondents interviewed in the selected study area Temperate-highland, Sub-humid and Semi-arid agro ecological zone demonstrated high degrees of knowledge, awareness and understanding of the concept of climate, climate variability and the likely causes of climate change on their local environments.

The majority of the participants have the information of climate variability before now as the Temperate-highland agro-ecology (13.8%), Sub-humid zone (17.1%), and Semi-arid agro-ecology (19.1%), of respondents were said that there was knowledge about climate variability, where as 12.4%, 14.9%, 22.4% not have information about climate variability respectively. The results show that out of 361 respondents 189 respondents equivalent to 52.3%, were aware of the factors responsible for climate variability where they associated the causes of the changing climate 25.7%, 29%, 45.1% for Temperate-highland, Sub-tropical, and Semi-arid agro ecologies have understanding about the cause that contribute for climate variability. The results revealed further that the proportion of the respondents who were aware of climate variability was higher in the Semi-arid agro-ecologic zone than in the Temperate-highland and Sub-tropical (Figure 5.1).

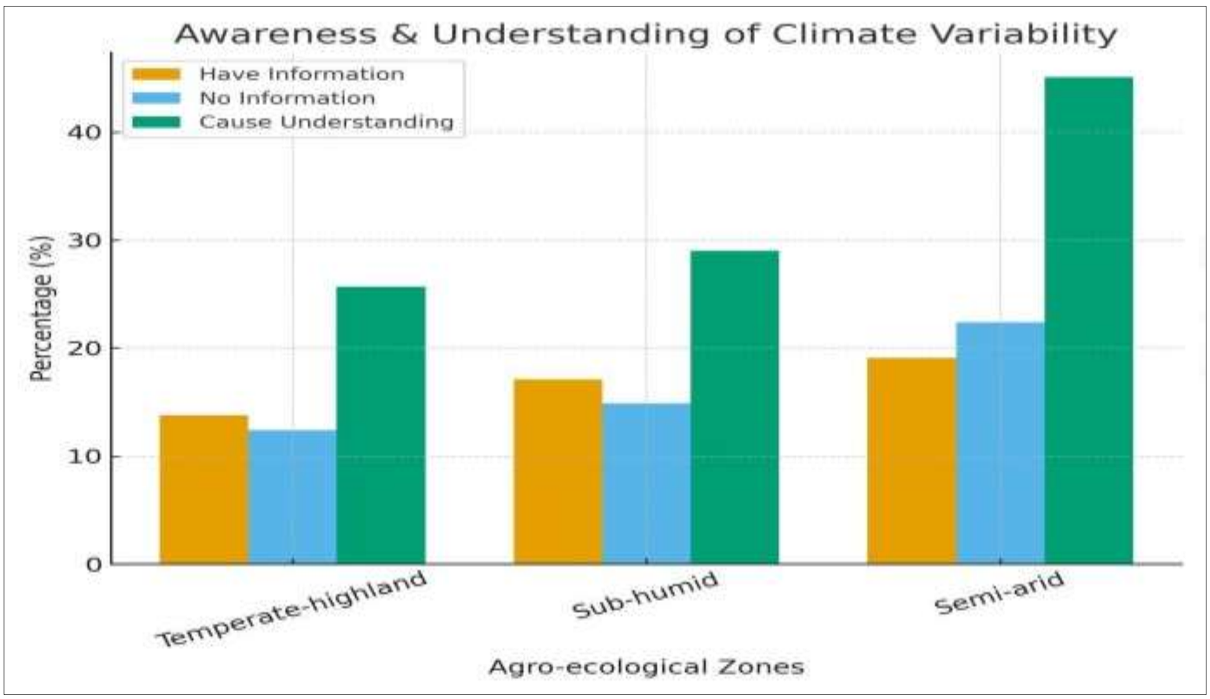


Figure 5. 1 Farmers perception of climate change cause across the three agroecological zones

The study revealed that farmers perceived multiple indicators of climate variability, particularly those related to changes in rainfall patterns. These indicators included a decline in rainfall over the past four decades; late onset and early cessation of the rainy season; rainfall at the beginning of the rainy season; rainfall during the planting and growing periods; timely cessation of rainfall; rainfall during the harvesting period; off-seasonal rainfall; changes in planting time to adjust to rainfall onset; and increased rainfall irregularity. Farmers' perceptions of these rainfall-related indicators varied across the three agro-ecological zones.

In the temperate highland agro-ecological zone, the proportions of farmers reporting these indicators ranged from 21.8% to 30.1%. In the sub-humid agro-ecological zone, the corresponding values ranged from 27.7% to 34.6%. The highest levels of awareness were observed in the semi-arid agro-ecological zone, where reported proportions ranged from 40.4% to 47.0% (Figure 5.2). Overall, farmers in the semi-arid zone exhibited a greater awareness of climate variability compared to those in the temperate highland and sub-humid zones. The differences in perceptions of climate change and variability among the three agro-ecological zones were statistically significant ($\chi^2 = 46.8$, $p < 0.001$).

One of the participants during focus group discussions in the Temperate-highland agro-ecological zones reported that "*for a successful harvest, planting should now be done with the immediate onset of the rain.* In addition, the participant explained further that *with variable rainfall concentrated within a short period of time, planting early when the soil is still wet helps crops to survive and to tolerate drought conditions until further rains arrive.*" However, this was reported to be successful only if drought tolerant hybrid seeds are planted. Another participant from the Semi-arid agro-ecological zones reported that, *"traditionally, the spring season rain was an alert for the starting point of the rainy season and the majority of the growing farmers would start field preparation to ready for planting at that time, while a few would sow their seeds to exploit early rains and benefit from the earlier harvest. However, nowadays farmers have abandoned such traditional practices, and instead the first rains are now used for crop sowing rather than farm preparation.*"

Similarly, changes in weather conditions have led to farmers abandoning early planting strategies when they used to scattered seeds on the ground a month earlier before the beginning of the rain. This was done in June in the Temperate-highland agro ecological zones and in some cases was supported by cool weather conditions, while sub-humid agro-ecological zones supported by traditional irrigation in areas with local rivers for their crops until the rainy season begun. In the semi-arid, seed planting was done during the time of farm preparations and some would begin germinating just with the presence of morning dew and survived until the first rain began.

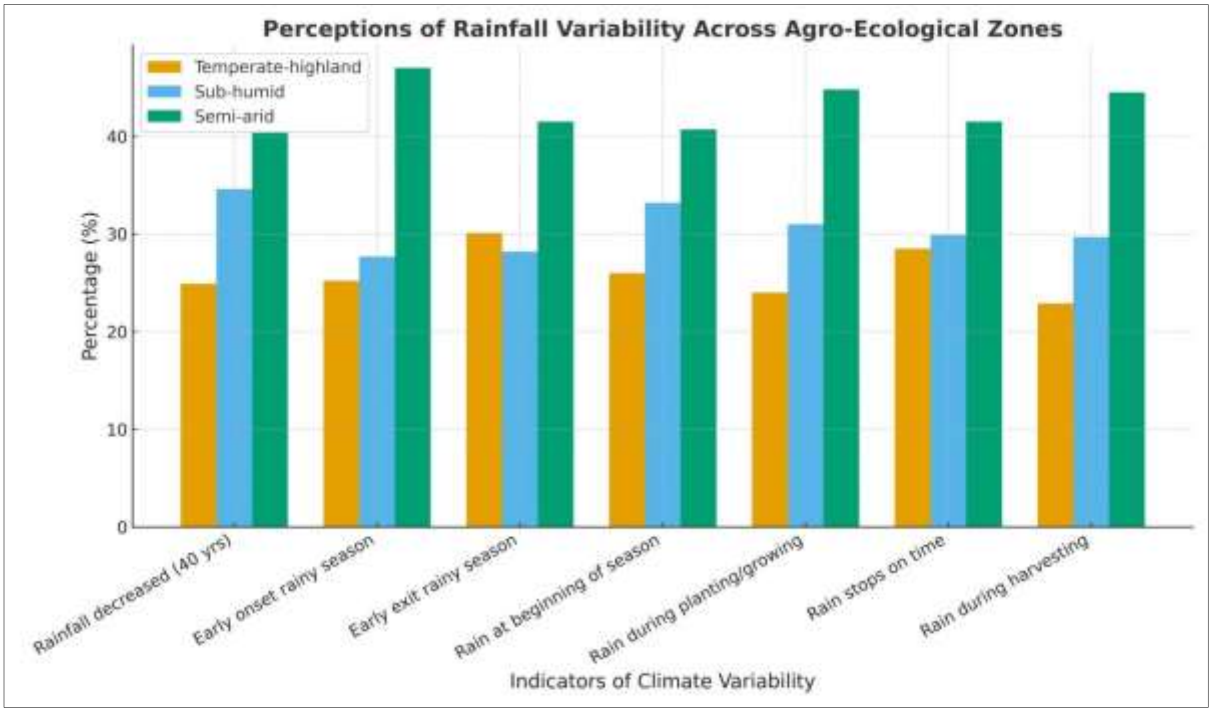


Figure 5. 2 Farmers perception of rainfall related indicators across the three agroecological zones

Farmers' perceptions of temperature-related indicators, including the increase in daily temperatures, rising temperatures over the past four decades, and the lengthening of months with high daytime temperatures, varied across the three agro-ecological zones.

In the temperate highland agro-ecological zone, 21.6% of respondents perceived an increase in daily temperatures, 18.0% observed a rise in temperatures over the last four decades, and 29.0% reported experiencing longer months with high daytime temperatures. In the sub-tropical zone, 28.5%, 32.9%, and 26.8% of respondents reported the respective indicators. In the semi-arid zone, perception was notably higher, with 49.8% of respondents recognizing an increase in daily temperatures, 49.5% noting rising temperatures over the last four decades, and 44.3% reporting longer periods of high daytime temperatures (Figure 5.3).

Overall, farmers in the semi-arid zone demonstrated the greatest awareness of temperature variability, likely because lowland areas are naturally hotter, making even marginal increases in temperature more noticeable. Statistical analysis confirmed that perceptions of temperature-related indicators differed significantly among the three agro-ecological zones ($\chi^2 = 22.8$, $p <$

0.001). This result has the same finding with the study by (Birhanie Addisu Bitew *et al.*, 2025), and (Dereje *et al.*, 2022).

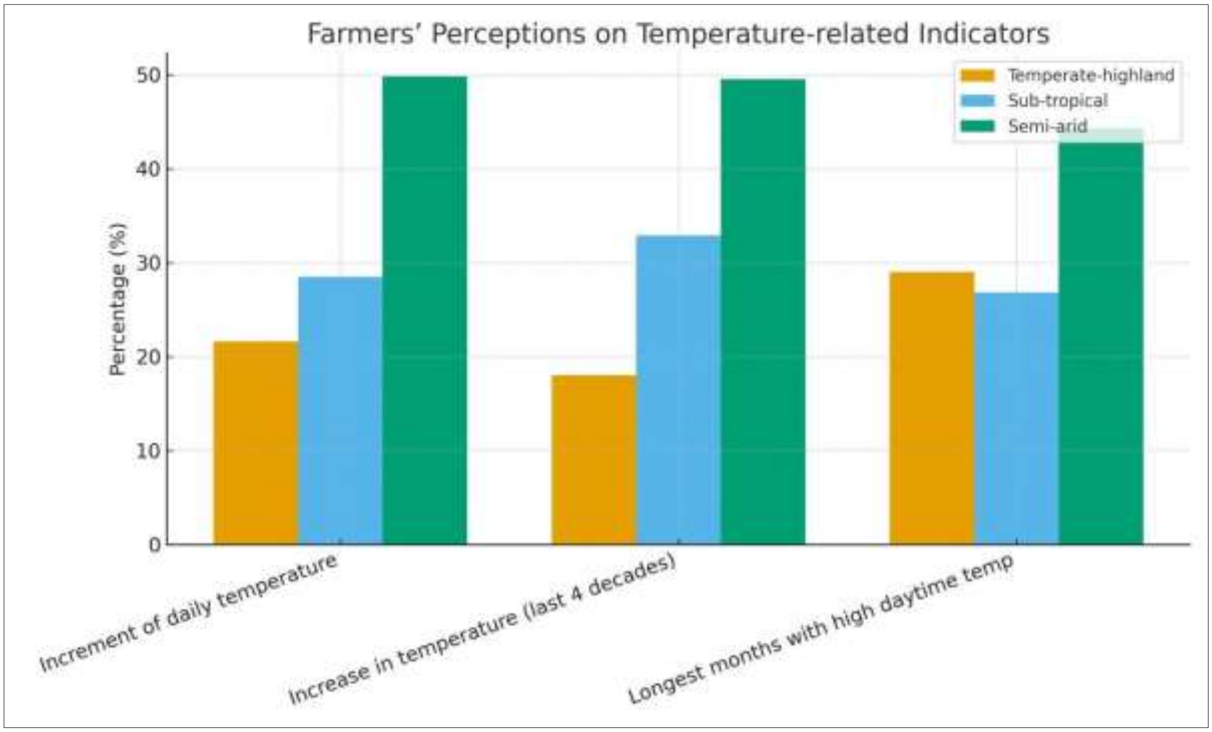


Figure 5. 3 Farmers perception of temperature related indicators across the three agroecological zones

Many respondents shared the views that in recent years they have noticed an increase in the intensity of sunshine which influences the surface temperature in their localities, in the three agro-ecological zones. Daily temperatures are perceived to have increased which also leads to an increase in the evening to midnight temperatures. Respondent from the Semi-arid agro-ecological zone was quoted that: *"nowadays, days and nights are very hot that I even do not use a bed sheet or blanket to cover myself during the night time due to the highest temperature, might be use early morning.*" Another respondents from Sub-tropical and Temperate-highland agro-ecological zones reported that "*nowadays the solar intensity has increased to the extent that at 9-10 am local time the sun is strong and 'stings' like that of the afternoon and mid*-day*."*

The respondent from Temperate-highland agro-ecological zone said that, "*nowadays there is no difference between Semi-arid and Temperate-highland agro-ecological zones based on temperatures, we now all experience almost the same degrees of heat and sunshine."* However, the majority of the respondents during focus group discussions and household interviews in the Temperate-highland agro-ecological zone perceived that temperatures have increased almost two times than in the past four decades. Similar observations have been in different parts of Ethiopia (Gadédjisso-Tossou, 2015; Adeoti *et al.*, 2016; Tesfaye *et al.*, 2016).

Crop disease pest infestation increases and becomes problem than earlier times, experience regarding crop failure over the last 40 years, experienced of coolness, frequent occurrence of drought in the past 4 decades climate variability/change in Temperate-highland 21.3%, 20.2%, 45.1%, 28.5%, Sub-tropical 28.2%, 32.9%, 31.0%, 31.0% and Semi-arid 50.4%, 47.3%, 45.9%, 45.1% respectively (Figure 5:3). The perception of farmers on crop disease pest infestation increases and becomes problem than earlier times, experience regarding crop failure over the last 40 years, experienced of coolness, frequent occurrence of drought in the past 4 decades climate variability/change indicators between the three agro-ecological zones is statistically significant ($\chi 2$ = 49.3 with P < 0.000).

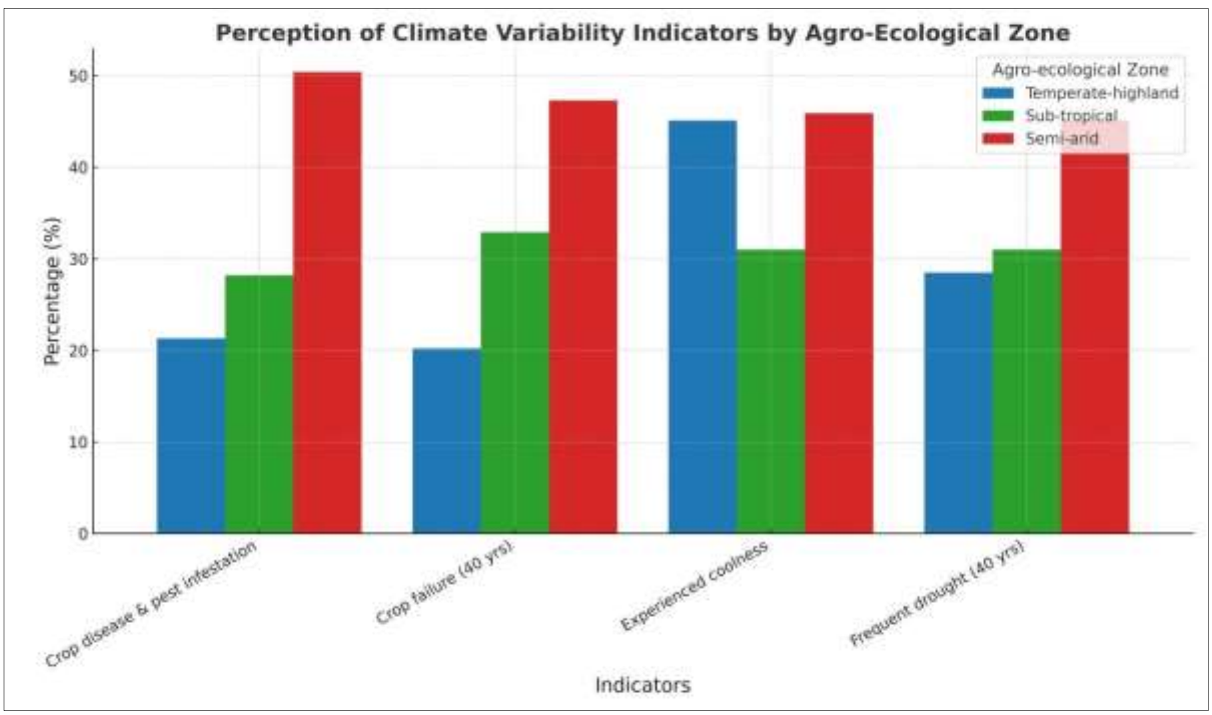


Figure 5. 4 Farmers perception of crop disease related indicators across the three agroecological zones

Heat-induced livestock disease, heat-induced human disease, Emergence of new plant species/invasive species in the form of weed, Some sources of livelihoods of the community are changing due to changing climate conditions as an indicator for climate variability for Temperate-highland agro ecological zone 28.5%, 24.3%, 22.9%, 30.7%, Sub-tropical 28.8%, 27.4%, 28.5%, 25.7% respectively. Semi-arid agro ecological zone 29.7%, 28.4%, 29.6%, 26.9% respectively (Figure 5:4). Heat-induced livestock disease, heat-induced human disease, Emergence of new plant species/invasive species in the form of weed, Some sources of livelihoods of the community are changing due to changing climate conditions as an indicator of climate change/variability between the three agro-ecological zones is statistically significant ($\chi2 = 11.9$ with $P < 0.011$).

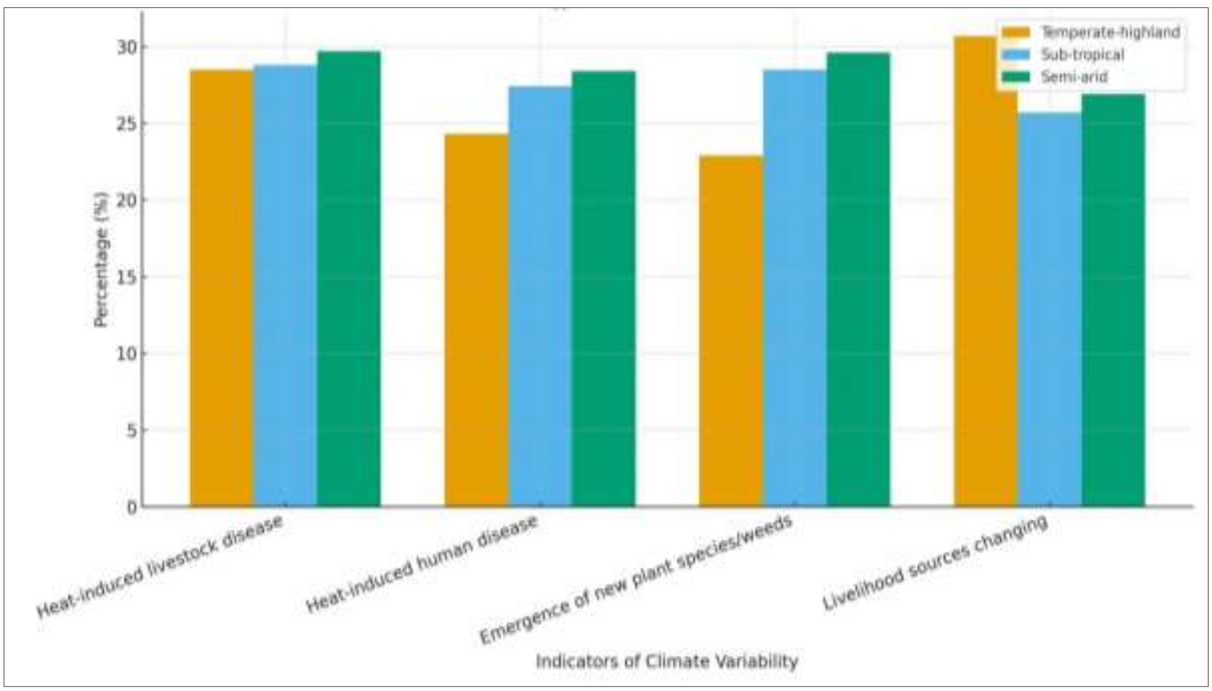


Figure 5. 5 Farmers perception of health related indicators across the three agroecological zones

From the Semi-arid agro-ecological zone focus group discussions participants revealed that "*there has been an increase in the population of pests, crop diseases and insects, compared to the past 40 years.*" They also associate the increase "*with the declining amount of rainfall, as higher rainfall was believed to cause more deaths of the pest and insect populations, while moderate rainfall and warm conditions encouraged the survival and proliferation of insects." Also, the limited availability of varieties of grasses for insects to feed on confined them to* *agricultural crops only. In addition, reliable rainfall speeds up the growth of crops making them less vulnerable to pest damage. One of the participants in the focus group discussions in Sub-humid agro-ecological zone reported that due to an increase in droughts and continued crop failures in the Semi-arid zones, many pests and insects have migrated to the Sub-humid zones."* Temperate-highland agro ecology zone farm observations and guided transect walks revealed that many of the crops in the highlands had been attacked by insects (grasshopper) and crop diseases (*Akenchira for maize*). This result finding has similarity for(UNDP, 2007b; Aklilu *et al.*, 2009).

Focus group discussions and interviews revealed that in the past drought incidences occurred, but they were rare and their occurrence took a sequential series over time to the extent that farmers were able to predict when another incidence of drought would occur. The drought incidences in the past four decades were reported to occur about every 7-10 years where the drought name represents the coping strategy opted for during that particular drought. However, the study revealed that, the majority of the participants perceived that in recent years, drought conditions have become more frequent and intense especially since the 1990s. Discussions with the three agro-ecological zone participants suggested that drought conditions in recent years occur almost in every season, or in consecutive years which result in increased crop failures and food shortages at the household level, especially in the Semi-arid agro-ecological zones highly venerable.

Drying of local ponds and springs, fluctuation of rivers and streams water volume, drying of wet lands, flooding in the past 4 decades as an indicator of climate variability for Temperate-highland respondents perceived by 22.9%, 21.0%, 22.7% and 30.4%, for Sub-humid zone respondents perceived by 31.0%, 31.0%, 31.0%, 31.5%, and Semi-arid zone respondents perceived by 45.9%, 45.1%, 46.2%, 37.3% were strongly agree that ponds and springs drying, drying of wetlands and flooding occur respectively within the past forty years (Figure 5:5). The difference in perception of drying of local ponds and springs, fluctuation of rivers and streams water volume, drying of wet lands, flooding in the past 4 decades as an indicator of climate change/variability between the three agro-ecological zones is statistically significant ($\chi2 = 44.1$ with $P < 0.000$).

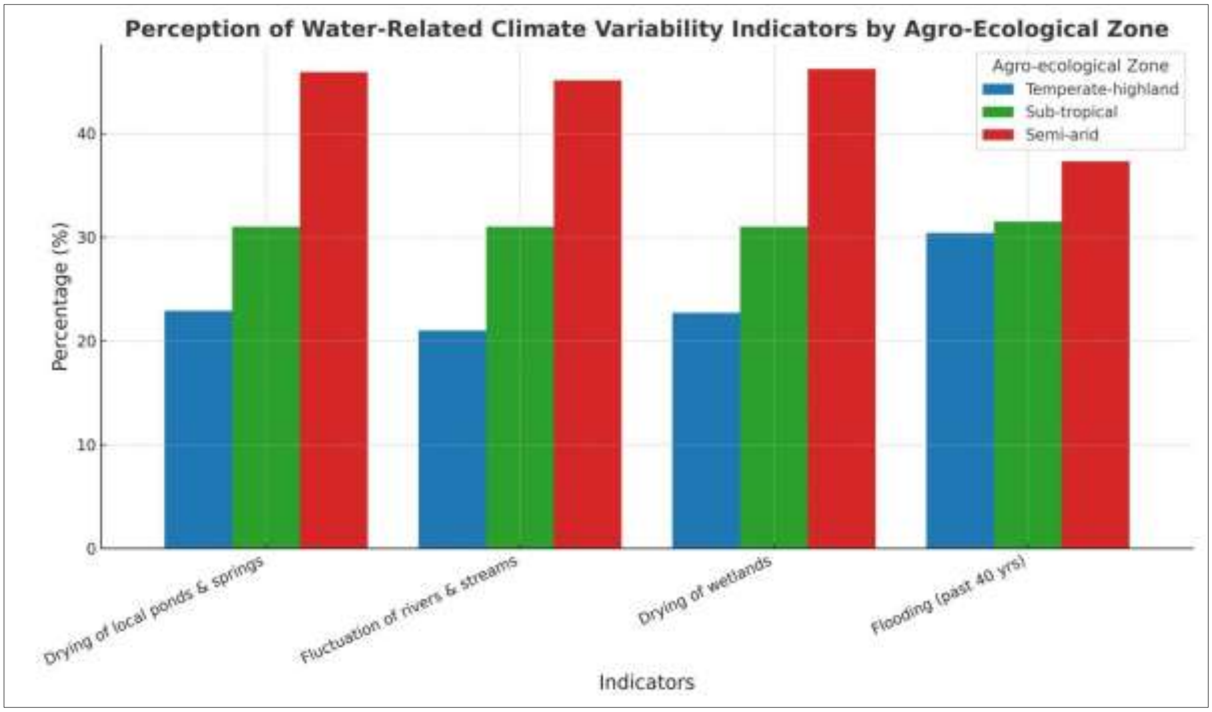


Figure 5. 6 Farmers perception of water related indicators across the three agroecological zones

Focus group participants from Semi-arid agro-ecological zones perceptions most of the participants suggested that "*the area has experienced a steadily decline in the amount of water in the local rivers and streams over the past forty years. They attribute this to rises in temperature and declines in rainfall, and increased rainfall variability. Some of the perennial rivers and streams have become seasonal, and others have dried out altogether."* In the Sub-tropical zone, participants reported that "*most of the rivers flowing from the Temperate-highland agro-ecological zone have become seasonal, as they now only flow during and shortly after the rainy season. From observations, most rivers and streams in the Temperate-highland agro-ecological zones had low volumes of water and some had dried, while in the Sub-humid and Semi-arid agro-ecological zones many river channels had dried (Figure 5:7)."* The photo was taken in the month of March, 2023 which is in between the winter *(dry season)* and summer *(large rainy season)*. This finding is supported by several studies which suggest that climate change will affect the future discharge and flow of many rivers and streams (Orindi *et al.*, 2005; Nyong *et al.*, 2007; Collier *et al.*, 2008).

Figure 5. 7 the dried river channel during the month of March taken during field time

Deforestation is becoming severe than earlier times to compensate the income loss by due to climate related problems and the community is migrating to cities due to inability of agriculture to support their livelihood, as an indicator of climate variability for Temperate-highland agro ecological zone 26.5% and 43.7%, for Sub-humid 29.3% and 27.9%, for Semi-arid 43.7% and 28.2% were strongly agree that deforestation and changing their livelihood respectively (Figure 5:8). The community is migrating to cities due to inability of agriculture to support their livelihood, deforestation is becoming severe than earlier times to compensate the income loss by due to climate related problems as an indicator of climate variability between the three agro-ecological zones is statistically significant ($\chi 2 = 33.9$ with $P < 0.000$).

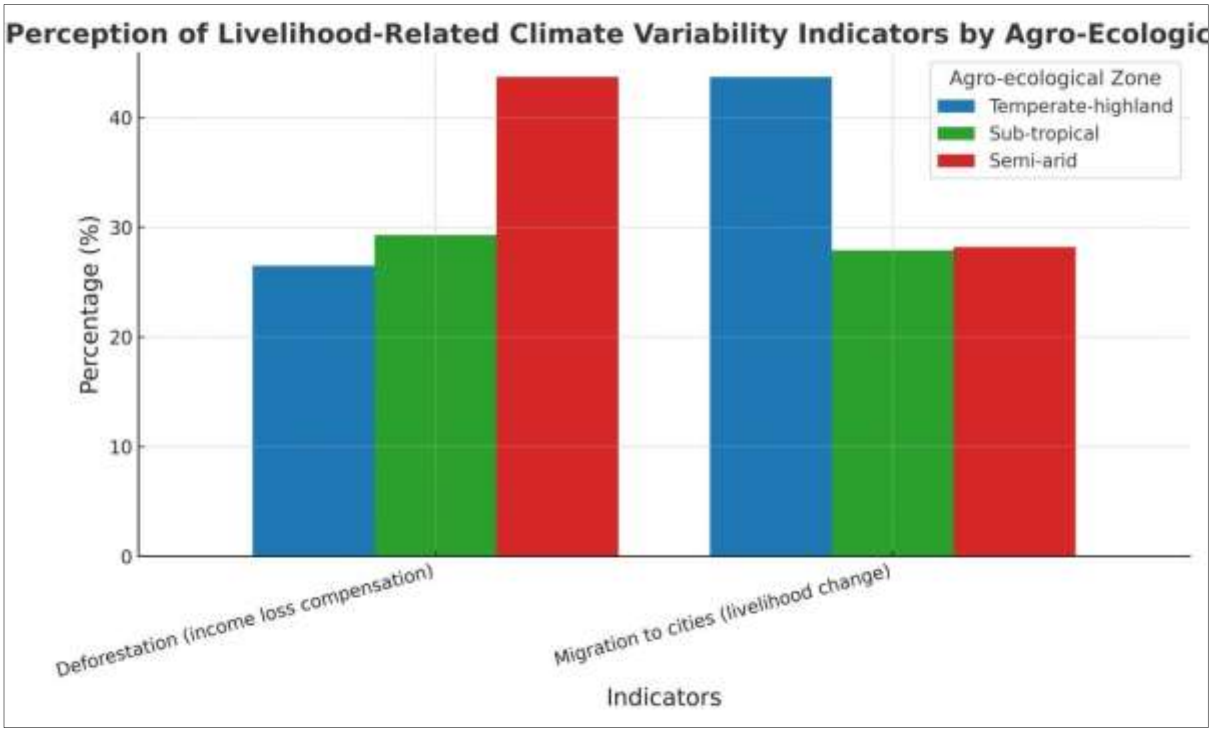


Figure 5. 8 Farmers perception of livelihood related indicators across the three agroecological zones

Key informant participants in the study area reported "*to have witnessed an increased occurrence of deforestation in almost every year for the past forty years. The deforestation incidences were said to have consumed significant parts of the forest reserves devastated those areas which had never previously been cleared since the forest grew. The decline in the thickness of the forest reserves caused by increased drought, luck of forage for their cattle and reduced the rate of surface cover, hence exposing land and water catchments to the direct sun rays which increase the rate of evaporation and evapotranspiration.*" Furthermore, from oral history interviews with the old age Key informant participant, *"it seems that water catchment sources had dried because of the removal of the surface cover forests and disturbances from human activities."* For instance, the participant reported that *"traditionally it is believed that forests considered as the house of their animals and birds, however due to lack of income from their crops due to climate variability the community used forests for charcoal production as a source of income."*

5.3.3 Analysis of Variance (ANOVA) for Farmers' Perception on Climate Change among Agro-Ecological Zones

Table 5.4 presents the results of the one-way analysis of variance (ANOVA) conducted to examine whether farmers' perceptions of climate change differ significantly among agro-ecological zones. The ANOVA results indicate a statistically significant difference in mean perception scores across the three agro-ecological zones ($F(2, 358) = 61.7$, $p < 0.001$).

The between-group sum of squares (60.49) is considerably larger relative to the mean square within groups (0.49), suggesting that a substantial proportion of the total variation in farmers' perception is explained by differences among agro-ecological zones rather than random variation within zones. This indicates that agro-ecological context plays a significant role in shaping farmers' perceptions of climate change.

The statistically significant F-value confirms that the variations observed in the descriptive analysis where higher perception levels were reported in semi-arid areas and lower levels in temperate highland areas are not due to chance. Therefore, the null hypothesis stating that there is no difference in farmers' perceptions of climate change among agro-ecological zones is rejected.

Overall, the ANOVA results demonstrate that farmers' perceptions of climate change vary significantly across agro-ecological zones, likely reflecting differences in exposure to climate variability, livelihood vulnerability, farming experience, and access to climate-related information.

Table 5: 3 Analyses Of Variance (ANOVA) for farmer's perception on climate change among different agro-ecological zones

Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	60.49	2	30.25	61.7	.000
Within Groups	175.3	358	0.49		
Total	235.8	360			

(* = significant at 0.05 level)

Table 5.5 presents the post-hoc pairwise comparison results of farmers' perceptions of climate change across the three agro-ecological zones. The findings indicate that farmers' perceptions differ significantly between some agro-ecological zones, while others show no statistically meaningful variation.

A statistically significant difference was observed between the temperate-highland and semi-arid zones (Mean Difference = −0.70, p = 0.000). The negative mean difference indicates that farmers in the temperate-highland zone have significantly lower perception scores compared to those in the semi-arid zone. This suggests that farmers in semi-arid areas may be more aware of climate change, possibly due to frequent exposure to drought, rainfall shortages, and climate-related livelihood risks.

The comparison between the semi-arid and sub-humid zones shows no statistically significant difference in farmers' perceptions of climate change (Mean Difference = 0.20, p = 0.071). This result implies that farmers in these two agro-ecological zones have relatively similar levels of climate change perception, with only minor differences that do not reach the 5% significance level.

In contrast, a statistically significant difference was found between the sub-humid and temperate-highland zones (Mean Difference = 0.90, p = 0.000). The positive mean difference indicates that farmers in the sub-humid zone exhibit significantly higher perception scores than those in the temperate-highland zone. This may be attributed to observable changes in rainfall patterns, crop performance, and seasonal variability in sub-humid areas.

Overall, the post-hoc analysis demonstrates that agro-ecological setting significantly influences farmers' perceptions of climate change, with farmers in semi-arid and sub-humid zones exhibiting higher perception levels than those in the temperate-highland zone. These findings highlight the importance of considering agro-ecological differences when designing climate awareness programs and adaptation strategies.

Table 5. 4 Post-Hoc Pairwise Comparison of farmer's perception on climate change among the three agro-ecological zones

(I) Zone	(J) Zone	Mean Difference (I–J)	Sig.
Temperate-highland	Semi-arid	-0.70*	.000
Semi-arid	Sub-humid	0.20	.071
Sub-humid	Temperate-highland	0.90*	.000

(* = significant at 0.05 level)

5.3.4 Results of the Binary Logit Model

In this section, a binary logistic regression model was employed to identify the determinant factors of farmers' perception of climate change. The Hosmer–Lemeshow test of model coefficients produced a Chi-square value of 0.000 with 6 degrees of freedom, which is insignificant at $p>0.05$ (Table 5-6). This indicates that the predicted and observed frequencies closely match, meaning there is no significant difference between them. Therefore, the estimates of the model fit the data at an acceptable level.

Table 5: 5 Logistic regression results for perception of farmers in different agroecological zones

Predictor	B (Coeff.)	Exp(B) = Odds Ratio	Sig. (p-value)
Age	0.012	1.012	0.021*
Gender (1=Male 0=Female)	0.420	1.52	0.048*
Education (0=can't read write 1= can read and write)	0.085	1.09	0.030*
Farming experience (years)	0.020	1.02	0.021*
Access to irrigation(1=user 0=non-user)	0.590	1.80	0.010*
Training (1acces to training 0=not get training)	1.120	3.07	0.000*
Formal weather forecasts (1=Access to information 0= Not access to information)	0.750	2.12	0.002*
Indigenous early warning(1=Practiced 0=Not practiced)	0.430	1.54	0.040*
Annual income (per 10,000 Birr)	0.065	1.07	0.070
Extension contact(1=has contact 0= not contacted)	0.090	1.09	0.015*
Off-farm activities (1=Yes 0= No)	-0.180	0.84	0.300
Semi-Arid Zone (1=Yes 0=No)	0.80	2.23	0.012*
Sub-Humid Zone (1=Yes 0=No)	0.45	1.52	0.040*
Constant	-2.400	—	0.000*

(* = significant at 0.05 level)

The binary logistic regression model was employed to identify factors influencing farmers' perception of climate variability and change. The results revealed that age, gender, education, farming experience, access to irrigation, training, and access to formal weather forecasts, indigenous early warning practices, extension contact, and agro-ecological zone significantly influenced farmers' perceptions, whereas annual income and participation in off-farm activities were not significant predictors.

Age had a positive and statistically significant effect on farmers' perception (B = 0.012, OR = 1.012, p = 0.021). This indicates that for every additional year of age, the odds of perceiving climate variability and change increased by approximately 1.2%, holding other variables constant. Older farmers are likely to have accumulated more life experiences and observations of climatic events, enabling them to better recognize climate-related changes.

Gender significantly influenced perception (B = 0.420, OR = 1.52, p = 0.048). Male-headed households were 1.52 times more likely to perceive climate variability and change than female-headed households. This may be attributed to greater access of male farmers to information, agricultural resources, and extension services.

Education had a positive and significant effect (B = 0.085, OR = 1.09, p = 0.030). Literate farmers were 1.09 times more likely to perceive climate variability and change compared with illiterate farmers. Education enhances the ability to access, interpret, and utilize climate-related information.

Farming Experience was positively associated with perception (B = 0.020, OR = 1.02, p = 0.021). A one-year increase in farming experience increased the odds of perceiving climate variability and change by 2%. Experienced farmers are more likely to compare current climatic conditions with past experiences and identify changes over time.

Access to Irrigation significantly increased the likelihood of perception (B = 0.590, OR = 1.80, p = 0.010). Farmers with irrigation access were 1.8 times more likely to perceive climate variability and change than non-users. Irrigation users tend to be more aware of rainfall variability and water resource challenges because of their greater involvement in water management.

Training emerged as the strongest predictor in the model (B = 1.120, OR = 3.07, $p < 0.001$). Farmers who received climate-related or agricultural training were approximately 3.07 times more likely to perceive climate variability and change than those who had not received training. Training improves awareness, knowledge, and understanding of climate risks and adaptation options.

Access to Formal Weather Forecast Information significantly influenced perception (B = 0.750, OR = 2.12, $p = 0.002$). Farmers with access to weather forecasts were 2.12 times more likely to perceive climate variability and change than those without access. Weather information enhances awareness of changing climatic conditions and helps farmers make informed agricultural decisions.

Indigenous Early Warning Practices also had a significant positive effect (B = 0.430, OR = 1.54, $p = 0.040$). Farmers who practiced indigenous forecasting methods were 1.54 times more likely to perceive climate variability and change than those who did not. This suggests that local ecological knowledge continues to play an important role in detecting environmental changes.

Annual Income showed a positive but statistically insignificant relationship with perception (B = 0.065, OR = 1.07, $p = 0.070$). Although higher-income farmers tended to be more likely to perceive climate variability and change, the effect was not significant at the 5% level.

Extension Contact had a positive and significant influence (B = 0.090, OR = 1.09, $p = 0.015$). Farmers who had contact with extension agents were 1.09 times more likely to perceive climate variability and change than those without such contact. Extension services facilitate information dissemination and awareness regarding climate-related issues.

Off-farm Activities had a negative but statistically insignificant effect (B = -0.180, OR = 0.84, $p = 0.300$). Farmers engaged in off-farm activities were 16% less likely to perceive climate variability and change; however, this effect was not statistically significant.

Regarding agro-ecological zones, farmers residing in the semi-arid zone were 2.23 times more likely to perceive climate variability and change than farmers in the temperate highland agro-ecological zone (B = 0.80, OR = 2.23, $p = 0.012$). Similarly, farmers living in the sub-humid zone were 1.52 times more likely to perceive climate variability and change compared with the temperate highland category (B = 0.45, OR = 1.52, $p = 0.040$). These findings indicate that farmers in relatively drier and more climate-sensitive environments are more aware of climatic changes due to their greater exposure to climate-related risks.

The negative and significant constant term (B = -2.400, $p < 0.001$) indicates a low baseline probability of perceiving climate variability and change when all explanatory variables are held at zero.

Overall, the findings suggest that institutional factors (training, extension services, weather information), resource access (irrigation), personal characteristics (age, education, farming experience), and agro-ecological conditions are key determinants of farmers' perception of climate variability and change in the study area.

5.4 Discussions

Studying how people in developing countries perceive the risks of climate change is essential because these nations require adaptable strategies to respond effectively to shifting environmental conditions. Farmers observed that average temperatures had risen and rainfall levels had decreased due to changes in the timing of the rains (Sraku-Lartey *et al.*, 2020). Similar findings have been reported in numerous studies conducted by scholars worldwide, which align closely with the results presented in this work (Asekun-Olarinmoye *et al.*, 2014; Akanbi *et al.*, 2021; Arıkan *et al.*, 2021). The results show that 52.3%, were aware of the factors responsible for climate variability where they associated the causes of the changing climate 25.7%, 29%, 45.1% for Temperate-highland, Sub-tropical, and Semi-arid agro ecologies have understanding about the cause that contribute for climate variability, this result in line with the study done by (Biswas *et al.*, 2021; Ebrahim *et al.*, 2022; Khatri *et al.*, 2023).

The study shows respondents responded that among the indicators of climate variability rainfall decreased for the past four decades, early onset and early exit of rainy season, rain at the beginning of the rainy season, rain during the planting and growing season, rain stops on time in the locality, rain during harvesting period, Off-seasonal rainfall, change in planting time/date to adjust to onset of rainfall, and erratic nature of rainfall were perceived by the farmers differently (Nhamo *et al.*, 2020; Akanbi *et al.*, 2021; Dias, 2022; Akano *et al.*, 2023).

Temperature related indicators increment of daily temperature, increase temperature the last 4 decades and longest months with high day time temperature farmers perceived in different understood across three agro-ecological zones (Capstick *et al.*, 2015; Chala *et al.*, 2020; Bourekba, 2021; Cheval *et al.*, 2022; Ebrahim *et al.*, 2022). The meteorological data revealed that the average annual temperature has been increasing steadily over the past 41 years. This indicates a rising trend in the average annual temperature with in the study area (see Fig. 5.5). This finding aligns with survey responses, where 91.9% of participants reported a temperature increase, corroborating earlier research findings (Minwuye, 2017). The study findings indicated that farmers residing in the Semi-arid agro-ecological zone area perceived greater climate changes compared to those in the Temperate-highland agro-ecological zones. This observation might be attributed to the recurrent drought occurrences in the region in recent years or to various environmental shifts leading to decreased water availability (Saguye, 2017; Sraku-Lartey *et al.*, 2020; Van Valkengoed *et al.*, 2022).

This study revealed that due to climate change the community perceived that Crop disease pest infestation increases and becomes problem than earlier times, experience regarding crop failure over the last 40 years, experienced of coolness, frequent occurrence of drought in the past 4 decades climate variability/change in Temperate-highland 21.3%, 20.2%, 45.1%, 28.5%, Sub-tropical 28.2%, 32.9%, 31.0%, 31.0% and Semi-arid 50.4%, 47.3%, 45.9%, 45.1% respectively (Karki *et al.*, 2020; Aidoo *et al.*, 2021; Akanbi *et al.*, 2021; Bourekba, 2021; Ebrahim *et al.*, 2022). Drought conditions in recent years occur almost in every season, or in consecutive years which result in increased crop failures and food shortages at the household level, especially in the Semi-arid agro-ecological zones highly venerable (Dias, 2022). Drying of local ponds and springs, fluctuation of rivers and streams water volume, drying of wet lands, flooding in the past

4 decades as an indicator of climate variability were increased (Karki *et al.*, 2020; Ruiz *et al.*, 2020). Crop disease pest infestation increases and becomes problem than earlier times, experience regarding crop failure over the last 40 years, experienced of coolness, frequent occurrence of drought in the past 4 decades climate variability/change (Elum *et al.*, 2017; Bourekba, 2021; Ebrahim *et al.*, 2022). Heat-induced livestock disease, heat-induced human disease, Emergence of new plant species/invasive species in the form of weed, Some sources of livelihoods of the community are changing due to changing climate conditions as an indicator for climate variability (Okonya *et al.*, 2013; Minwuye, 2017; Mkonda *et al.*, 2018; Aidoo *et al.*, 2021; Akanbi *et al.*, 2021).

5.5 Future work

This study has provided valuable insights into farmers' perceptions of climate variability across agro-ecological zones in Jabitehinan district. However, several areas remain open for further research. Longitudinal Studies, Future research should employ panel or time-series data to better capture how farmers' perceptions evolve over time in relation to changing climate patterns. Integration of Scientific Climate Data, Combining farmers' perceptions with meteorological and satellite-based climate data could strengthen the analysis by aligning subjective experiences with objective climate records. Broader Geographic Coverage, Expanding the study to multiple districts or regions in Ethiopia would allow for comparative analysis and generalization of findings across diverse agro-ecological zones. Policy and Adaptation Linkages, Further studies should focus on how farmers' perceptions influence their adaptation practices and decision-making. This would help policymakers design locally appropriate climate adaptation strategies. Socio-cultural Dimensions, Given the significant proportion of respondents attributing climate variability to religious or supernatural factors, more in-depth qualitative research is needed to understand how cultural and belief systems shape climate risk perception. Gender and Youth-focused Studies, since gender was identified as a significant factor influencing perception future research should explore the differentiated experiences of men, women, and youth in climate variability adaptation. Impact on Livelihoods and Food Security, Further studies can examine the direct link between climate variability perception, actual adaptation measures, and their outcomes on household income, crop yields, and food security. Climate Information Systems, Research on the effectiveness of indigenous early warning systems and formal forecasts, including the integration of ICT-based tools, could provide valuable insights for improving climate communication strategies. By addressing these gaps, future research can contribute to a more comprehensive understanding of climate variability perceptions and support the development of targeted interventions that enhance farmers' resilience to climate change.

5.6 Conclusion

This study examined farmers' perceptions of climate variability across different agro-ecological zones in Jabitehinan district, North West Ethiopia, and highlighted the diverse ways in which local communities experience and interprets changes in climate. The results revealed that perceptions of climate variability were not uniform but varied significantly by agro-ecological zone, with semi-arid households showing the highest awareness of both rainfall and temperature-related changes. A considerable share of respondents attributed climate variability to religious or supernatural causes, while others associated it with natural and human factors, reflecting the interplay between cultural beliefs and scientific understanding.

The findings further demonstrated that perceptions were shaped by socio-demographic and institutional factors such as gender, education, irrigation access, and training, access to forecasts, indigenous early warning systems, and extension contact. These factors proved more influential than age, farming experience, income, or off-farm activities, suggesting that information access and institutional support play a greater role in shaping climate awareness than personal characteristics alone.

Overall, the study underscores the importance of understanding local perceptions as a foundation for designing effective climate adaptation strategies. Policymakers and development practitioners should recognize the heterogeneity of perceptions across agro-ecological zones and integrate both scientific and indigenous knowledge systems when promoting adaptation. Strengthening climate information dissemination, enhancing education and training, and fostering inclusive extension services will be critical in bridging perception gaps and enabling farmers to make informed decisions that enhance resilience to climate variability.

5.7 Policy Implications

The findings of this study highlight the need for policies that strengthen farmers' adaptive capacity to climate variability by addressing the socio-demographic and institutional factors that shape perception. Since education, irrigation access, training, extension services, and access to both formal forecasts and indigenous early warning systems significantly influenced perception, policies should prioritize expanding rural education and capacity-building programs, investing in small-scale irrigation infrastructure, and improving the accessibility and reliability of climate information. Efforts must also be tailored to local realities, as perceptions varied significantly across agro-ecological zones, implying that uniform policies may be ineffective. The substantial proportion of respondents attributing climate variability to religious or supernatural causes underscores the importance of integrating awareness campaigns that respect cultural beliefs while enhancing scientific literacy. Moreover, gender-sensitive climate policies are essential to ensure equitable access to information and resources, as gender was found to be a key determinant of perception. Overall, policy interventions should aim to bridge knowledge gaps, enhance localized adaptation strategies, and promote inclusive and sustainable approaches that empower farming communities to respond effectively to climate change.

5.8 Recommendation

Based on the findings of this study, it is recommended that interventions aimed at enhancing farmers' resilience to climate variability should prioritize improving access to accurate and timely climate information through both modern forecasts and indigenous early warning systems. Strengthening education, training, and extension services is essential to build farmers' capacity to interpret climate signals and adopt appropriate adaptation practices. Given the significant influence of gender on perception, climate policies and programs should be designed in a way that is inclusive and sensitive to the needs of both men and women, while also creating space for youth engagement. Efforts should also focus on promoting irrigation and other sustainable water management practices to reduce dependence on increasingly erratic rainfall patterns. Moreover, since a considerable proportion of farmers associate climate variability with religious or supernatural causes, awareness-raising campaigns that integrate scientific knowledge with respect for cultural and belief systems are necessary to bridge gaps in understanding. Policymakers and development practitioners should also tailor strategies according to the unique challenges and perceptions within each agro-ecological zone, as differences across zones were found to be statistically significant. In doing so, interventions will be more context-specific and effective in fostering adaptive capacity and ensuring sustainable livelihoods in the face of climate change.

Chapter Six

Assess church forest species diversity and its regeneration status in different agro-ecological zones of Jabitehinan district, North Western of Ethiopia[4]

6.1 Introduction

The Ethiopian Orthodox Tewahido Church's and monasteries frequently nestle within small natural forests distinguished by rich floral and faunal diversity, boasting numerous indigenous and rare species (Wassie *et al.*, 2006b; DistictAgricultureoffice, 2020; Maru *et al.*, 2023). In Ethiopia, there are two types of church forests. The first type consists of churches that are over five hundred years old, and these are surrounded by primary forests. On the other hand, the second type includes recently established churches from the last few decades, and these are surrounded by secondary forests. In the case of the older church forests, they exhibit a notable abundance of both plant and animal species, including many indigenous and rare varieties (Wassie *et al.*, 2006b). These closely located forests have high ecological importance to form corridors and are important for species exchange and the distribution of genetic resources in conservation (DistictAgricultureoffice, 2020; Maru *et al.*, 2023). Church forests are the ideal sites to be chosen for species afforestation programs in their specific localities and that could serve as models of biodiversity conservation. Numerous endangered flora species in Northern Ethiopia thrive in the vicinity of churches and monasteries (Tilahun *et al.*, 2015b). The Ethiopian Orthodox Tewahido Church is making a sustained effort to teach and advise the clergy and the people living in the community; highlight the need to protect existing trees; induce the desire to plant and look after newly planted trees, and in particular care of indigenous trees and plants (Wassie *et al.*, 2006b). The church forests are the sanctuary of many indigenous species protected in different climatic zones, could be used as germplasm for regeneration and then to conserve biodiversity (Tilahun *et al.*, 2015b).

---

[4]Accepted for Publication and under Production in the journal of Sustainability

The Ethiopian Orthodox Tewahido Church forests are often safe places for trees and other biodiversity resources. In other words, church compounds are serving as in situ conservation and hot spot sites for biodiversity resources, including many endemic and endangered species (Wassie *et al.*, 2006b; Tura *et al.*, 2013; Tilahun *et al.*, 2015b; Mucheye *et al.*, 2020).

Ethiopia with its large spatial difference and because of its high edaphic, weather, rugged topography and altitudinal difference has a mixed life (FAO, 2015). Although there is debate between the coverage of the last decade forest coverage in Ethiopia, historical sources indicate that some thirty-five up to forty percent of the earth coverage might have been once covered with forests (FAO, 2015). As the result of high demand of agriculture land cutting down of forests, large size of forests coverage have been disappeared, this phenomenon still continue in the high speed, nearly 141,000 ha (0.93%) of the forest cover was damaged each year (FAO, 2015). The present day merely forest patches, present as remnant indigenous forests found around churches and monasteries under traditional conservation effort of the Ethiopian Orthodox Tewahido Churches (Wassie *et al.*, 2006b; Tilahun *et al.*, 2015b). The EOTC has a good culture for forest conservation practice around the surrounding of its Monastry and church due to religious thought and believers pay more attention to protect and conserve the forest (Wassie *et al.*, 2010).

The increment of people number and high interest on the natural resources like forest outputs, has been minimize the mean occupied area of forest resource in the churches surroundings (Scull *et al.*, 2017; Cardelús *et al.*, 2019). The root cause for decreasing of forest coverage in our country are high demand of agricultural land, demand of wood for cooking and house construction, furniture production, and using charcoal as a trade goods (Shibru *et al.*, 2004).

The diversity of species in church forests can be influenced by various factors, including the agro-ecological zone in which they are located. Agro-ecological zones are characterized by specific climate, soil, and vegetation patterns, and these factors can affect the types of species that thrive in a particular area. Different agro-ecological zones have different temperature and precipitation patterns, which can influence the types of plants and animals that can thrive in a particular area. Some species may be adapted to specific temperature ranges or moisture levels. Soil composition varies across agro-ecological zones, affecting plant growth. Some species may be adapted to specific soil types, and the diversity of plant species in church forests can be influenced by soil fertility, texture, and nutrient content. Agro-ecological zones often exhibit different vegetation types, such as grasslands, savannahs', or forests. These vegetation types can influence the types of species present in a given area. The impact of human activities, such as agriculture and land use practices, can vary across agro-ecological zones. These activities can affect the diversity of both plant and animal species in church forests. The geographic location of church forests within an agro-ecological zone can also play a role. Proximity to other natural habitats, migration routes, and connectivity with larger ecosystems can influence species diversity. To study and understand the species diversity in church forests across different agro-ecological zones, researchers typically conduct ecological surveys. These surveys involve documenting the presence and abundance of various species, studying their interactions, and assessing environmental variables that may influence biodiversity.

The primary objective of this research is to assess the composition, diversity, structure, and regeneration status of woody species in church forests of the Jabitehinan district, North West Ethiopia, in order to understand their ecological significance and conservation potential across different agro-ecological zones, while the specific objectives are to identify and document the species composition and taxonomic distribution of woody plants in selected church forests, to analyze the species diversity and evenness using Shannon-Wiener and related diversity indices, to evaluate the structural characteristics of woody species in terms of family dominance and diameter at breast height (DBH), to assess the regeneration status of woody species through seedlings, saplings, and mature tree ratios, and to compare phyto-geographical similarities among church forests across semi-arid, sub-humid, and temperate highland agro-ecological zones.

Accordingly, the research questions guiding the study are what are the species composition and family distribution of woody plants in the church forests of Jabitehinan district?, how diverse and evenly distributed are woody species in the studied church forests?, which plant families are dominant in each church forest and how their structural composition differs?, what is the regeneration status of woody species based on the ratios of seedlings, saplings, and mature individuals?, and how similar are church forests in terms of woody species composition across different agro-ecological zones?.

No research has been conducted in the specified district regarding the evenness, diversity, structure, and conservation status of church forests in the Jabitehinan district. Hence, it is imperative to undertake this study to thoroughly assess and record the species evenness, composition, diversity, structure, and regeneration status of church forests in the designated area. Furthermore, the study aims to furnish valuable information and recommendations for the effective management, sustainable utilization, and conservation of the district's church forests.

6.2 Data Source and Sampling

Data on species composition were gathered from twenty sample plots within three church forests, each measuring 15 x 15m, with a focus on recording the number of trees per species. In cases where distinct canopy layers are observable, separate sampling was conducted to aid species identification. The identification process was carried out for each canopy layer, starting with trees exceeding 20m in the first layer, followed by those between 10 and 20m in the second layer, and trees under 10m in the third layer. Within each 15 x 15m plot, there were a nested subquadrat of 10 x 10m for sampling shrubs taller than 1m, and a further nested subquadrat of 5 x 5m for sampling dominant herbs, tree regrowth, and shrub species under 1m (Figure 6.1). The biological composition of plants in the study area was characterized by the presence of trees, shrubs, and dominant herbs within the sampling quadrats. Local names of woody plant species and their individual counts were meticulously documented.

6.3 Data analysis

6.3.1 Structural data analysis

Vegetation structure, diversity, and evenness were characterized using various metrics, including the Shannon Diversity Index, Simpson Diversity Index, Sorenson’s similarity index, species density, Diameter at Breast Height (DBH), height, basal area, frequency, and Important Value Index (IVI).

The Shannon index, an information statistic index, assumes that all species are represented in a sample and that they are randomly sampled (Shannon & Weaver, 1949). It is calculated using the formula:

$$Shannon\ Diversity\ Index(H) = -\sum_{i=1}^{s} pi \ln(pi)$$

Where

H= Shannon diversity Index

S= the total number of species in the community (species richness)

Pi= the proportion of individuals (or abundance) of the i-th species, calculated as ni/N, Where ni is the number of individuals of species i, and N is the total number of individual of all species.

ln (pi) = the natural logarithm of pi

The Simpson index is a dominance index that gives more weight to common or dominant species (Mucheye et al., 2020). It is calculated using the formula:

$$Simpson\ Diversity\ Index = 1 - \sum_{i=1}^{s} p2\,i$$

Where

S= the total number of species (species richness)

pi= the proportion of individuals (or abundance) of the i-th species, calculated as ni/N, Where ni is the number of individuals of species i, and N is the total number of individual of all species.

Density refers to the number of individual plant species within quadrats, calculated by converting the count from the sample plot to a hectare basis using the formula:

Density (D) = Number of individuals of a species in the sample

Sample area in hectare

Relative density is calculated as:

$$\text{Relative density (RD)} = \frac{\text{Number of individuals of a species}}{\text{Total number of individuals of all species}} *100$$

Frequency (F) is the number of plots occupied by a given species per total number of plots laid out, often expressed as a percentage:

$$\text{Frequency (F)} = \frac{\text{Number of plots in which a species occur}}{\text{Total number of plots laidout}} *100$$

$$\text{Relative frequency (RF)} = \frac{\text{Frequency of a species}}{\text{Sum of frequencies of all species}} *100$$

Basal area (BA) is the cross-sectional area of tree stems at breast height (1.3 m above ground level) and is calculated using the formula:

$$BA = \frac{\pi d^2}{4}$$

Dominance (DO) is the total cover or basal area of species A divided by the area sampled, while relative dominance (RDo) is calculated as:

$$\text{Relative Dominance (RDo)} = \frac{\text{basal area of a species}}{\text{Total basal area of all species}} *100$$

The Important Value Index (IVI) is calculated as the sum of relative dominance (RD), relative density (RD), and relative frequency (RF):-

IVI = RD + RF + RDo

Sorenson's similarity index is calculated using the formula:

$$\text{Sorenson's Similarity index} = \frac{2c}{a + b}$$

Where c = the number of species common to both habitats, a = number of species in the first habitat and absent from the second, b = number of species in the second habitat and absent from the first. The values of Sorenson's similarity index always between 0 to 1, "0" indicated that there is no similarity species or overlapped species among the two compared areas, whereas "1" indicated that exactly the same species are found between the two compared communities.

6.3.2 Analysis of regeneration status of forests

The assessment of the regeneration status of woody species in forests involved a comparison of density values for seedlings, saplings, and matured woody plants within sacred groves, as conducted by (Dhaulkhandi *et al.*, 2008). According to the findings reported by Dhaulkhandi *et al.* (2008) and Kuma *et al.* (2015), a favourable regeneration status is indicated when the density follows the pattern seedlings > saplings > adults. If the density distribution is such that seedlings are greater than or equal to saplings and both are less than adults, the regeneration status is considered fair. Conversely, poor regeneration status is attributed when a species survives only in the sapling stage, and a lack of regeneration is inferred if a species is present solely in adult form.

6.3 Result and Discussion

6.3.1 Plant composition

The total of 49, 35 and 21 species were identified and registered from Awunt Abo monastery, Zengebal Bedega Giorgis church forests, and Guanesa Medhanialem Monastry respectively (Appendix 1). From all the species identified in the sample quadrants, 35 species were trees, 14 species were shrubs, 4 species were trees/shrubs, 1 species were climbers, 1 species were epiphytes and 1 species were Herbs (Appendix 1). The most diverse families were *Fabaceae* (7 species), *Asteraceae* (3 species), *Poaceae* (6 species), *Lamiaceae* and *Solanaceae* (5 species each), *Euphorbiaceae* (3 species) and seven other families were represented by 3 species each (Appendix 1). This finding has similarity with (Birhanu *et al.*, 2021) and (Alemneh, 2021) that done within the sub-humid agroecological zone in Dangila and Yilmana Densa and Quarit Districts, West Gojjam, Western Ethiopia church forest.

6.3.2 Species Diversity and Evenness

The overall Shannon-Wiener diversity of woody species in Awunt Abo monastery, Guanesa Medhanialem Monastry and Zengebal Bedega Giorgis church forests was 3.28, 2.75, and 2.57 whereas evenness was 0.54, 0.48, 0.74 and 0.82 respectively (Table 6.1and Figure 6.1). This result indicating that the diversity and evenness of woody species in the forest is relatively high. About 48.1% of woody plant species in the forest were under 1% of relative abundance and rare to find. Therefore, they fall on rare cover classes. About 46.2% of the woody species were categorized under common cover classes. Only 5.8% of woody plant species were categorized under abundant cover classes. Sorenson’s similarity analysis revealed moderate floristic similarity among the three church forests (0.54–0.64), with the highest similarity observed between Guanesa Medahinalem and Zengebal Bedega. Awunt Abo, while more species-rich, exhibited relatively lower similarity, indicating greater species uniqueness and ecological heterogeneity. These forests exhibit relatively higher diversity and evenness compared to the Weiramba forest in North Ethiopia, which had values of 2.3 and 0.66, respectively (Teshager *et al.*, 2018), and the Tara Gedam church forest, with values of 2.98 and 0.65, respectively (Zegeye *et al.*, 2011) (Zegeye et al., 2011). This indicates that the forest was predominantly populated by small-sized trees and shrubs, suggesting significant disturbance and habitat degradation among the woody plants in the area.

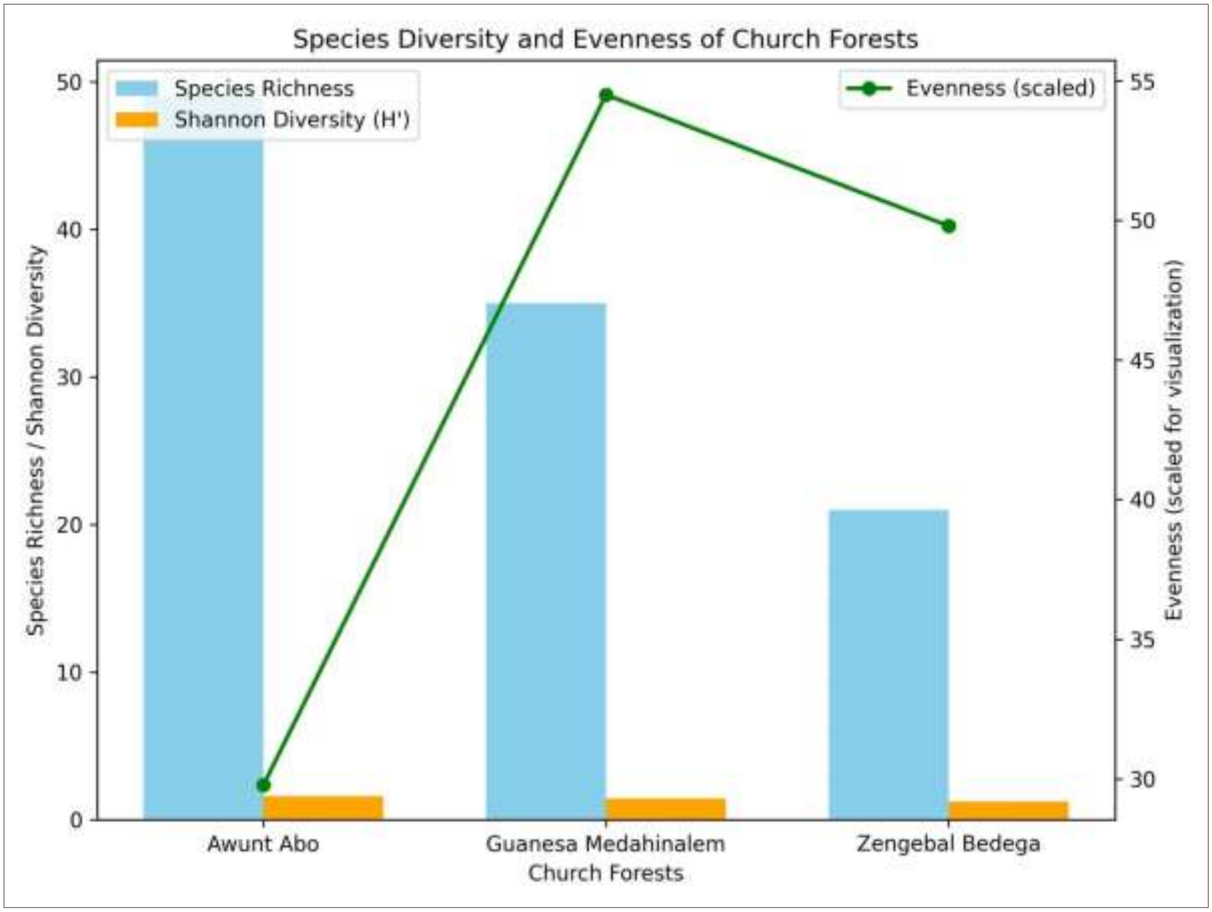


Figure 6. 1 Species diversity and evenness among the three agroecological zones

Table 6. 1 species diversity and evenness index for the three church forests

	Awunt abo Monastry	Zengebal Bedega Giorgis church	Guanesa Medahinalem Monastry
Taxa_S	49	35	21
Individuals	832	96	185
Dominance_D	0.04962	0.09084	0.07768
Simpson_1-D	0.9504	0.9092	0.9223
Shannon_H	3.289	2.837	2.756
Evenness_H'/ln(S)	0.5474	0.4877	0.7495

6.3.3 Frequency

The most frequently distributed family were different from forest to forest in the sampled monasteries (Shibiru *et al.*, 2004). Awunt abo monastery forests were dominated by *Euphoriaceae* (10.45%), *Mimosoideae* (8.77%), and *Cupressaceae* (7.57%), *Boraginaceae* (16.2%), and *Fabaceae* (14.20%), Guanesa Medhanialem Monastry forest were dominated by *Oleaceae* (14.59%), *Euphoriaceae* (8.9%), and *Cupressaceae* (8.10%), and Zengebal Bedega Giyorgis church forests were dominated by *Oleaceae* (17.70%), *Cupressaceae* (15.62%), and *celastraceae* (10.41%) (Appendix 3). Based on the description of the percentage frequency of the present study revealed that higher degree of large plants heterogeneity and at the same time there were forests have high number of species in the lower frequency (Teshager *et al.*, 2018).

6.3.4 Height distribution

The individuals of woody plant species in the study area were classified into six height classes: Class I (1–10 m), Class II (10–20 m), Class III (20–30 m), Class IV (30–40 m), Class V (40–50 m), and Class VI (>50 m).

The results revealed that Awunt Abo Monastery forest had the highest number of individuals in height class III (20–30 m), with 179 individuals, accounting for 21.5% of the total individuals recorded. This was followed by height class V (40–50 m) with 134 individuals (16.1%). In contrast, height class VI (>50 m) contained the lowest number of individuals (25), representing only 3% of the total population (Appendix 3).

In Guanesa Medhanialem Monastery forest, the highest number of individuals was recorded in height class III (20–30 m), with 59 individuals (31.8%), followed by height class I (1–10 m), which accounted for 57 individuals (30.8%). No individuals were recorded in height classes IV (30–40 m) and VI (>50 m), indicating the absence of taller trees in this forest (Appendix 3).

Similarly, Zengebal Bedega Giorgis Church forest exhibited the highest number of individuals in height class V (40–50 m), with 24 individuals (25%), followed by height class III (20–30 m), which contained 23 individuals (23.9%). No individuals were recorded in height class VI (>50 m) (Appendix 3).

Overall, the dominance of woody plant individuals in the lower and middle height classes suggests a scarcity of mature and tall tree species. This pattern may indicate selective cutting of large trees, particularly those within higher height classes, as reported by (Teshager *et al.*, 2018). Furthermore, the density of woody plants decreased gradually from lower to higher height classes, implying strong anthropogenic pressure such as selective harvesting for charcoal production, construction materials, and timber. As a result, the forests are dominated by small- to medium-sized individuals, reflecting high regeneration rates but limited recruitment into higher height classes. Similar findings have been reported in Gelawoldie community forest in northwestern Ethiopia (Mucheye *et al.*, 2020).

6.3.5 Diameter at Breast Height (DBH)

The distribution of woody plant individuals across Diameter at Breast Height (DBH) classes showed clear variation among the church forests (Appendix 3). Among the six DBH classes considered, Guanesa Medhanialem Monastery forest exhibited a strong dominance of large-diameter individuals, with 71.4% of the total recorded plants (238 individuals) falling within the highest DBH class (>50 cm).

Similarly, Awunt Abo Monastery forest was dominated by large-diameter trees, with 71.9% of individuals (594 plants) recorded in the highest DBH class (>50 cm). In contrast, 28.6% of the individuals (133 plants) were found in Zengebal Bedega Giorgis Church the smallest DBH class (<10 cm), indicating the presence of younger or regenerating individuals alongside mature trees.

The dominance of large-sized individuals across the church forests is consistent with findings reported by (Getaneh *et al.*, 2015) and aligns with results from previous studies conducted in similar forest ecosystems (Ahammad *et al.*, 2019; Ayalew *et al.*, 2020; Debebe *et al.*, 2023). This DBH structure suggests that church forests play a crucial role in maintaining mature tree populations, which is particularly important for carbon storage and sequestration. However, the long-term contribution of these forests to ecosystem services depends on effective conservation and sustainable management to ensure continued recruitment and forest stability. Individuals with multiple stems, all stems originating below breast height (1.3 m) were measured individually.

6.3.6 Importance Value Index (IVI)

The important value index (IVI) of each woody plant species in these church forests within the three agroecological zones were varied greatly, ranging from 1.2 to 46.4% of the church found within the semi-arid agro ecological zones Awuntabo monastry (Appendix2). From 0.0001 to 43.3% of the church found within the sub-humid agro ecological zones Guanesa Medahnialem monastry forest. From 4.1 to 70.2% of the church found within the temprate- highland agro ecological zones Zengebal Bedega Giyorgis church forest (Appendix2). More than 69.2% of the woody plant species had higher IVI (greater than 5%) within the Awunt abo monastry while the remaining 31.7% of the species had lower IVI which is lower than 5% (Appendix2). Under sub-humid agro-ecological zone found Guanesa medhanialem monastry more than 84.8% of the woody plant species had higher IVI (greater than 5%) while the remaining 26.2% of the species had lower IVI which is lower than 5%.

The five most important tree species in Awuntabo monastry forests under semi-arid agro-ecological zone were *Juniperus procera*, *Ficus vasta*, *Acacia siberana, Calpurnia aurea,* and *Maytenus arbutifolia*, were the most important species (Figure 6.2). Zengebal Bedega Giyorgis church under temprate-highland agro-ecological zone were *Juniperus procera*, *Olea europaea*, *Acacia abyssinica*, *Croton macrostachyus*, and *Maytenus arbutifolia,* Guanesa Medahinalem Monastry under Sub-humid agro-ecological zone were *Ficus vasta*, *Juniperus procera*, *Olea europaea, Acacia abyssinica*, and *Gnttiaflginea* (Appendix2). The Importance Value Index (IVI) analysis aids in prioritizing conservation efforts (Shibru *et al.*, 2004). Species with lower IVI values require intensive conservation measures, whereas those with higher IVI values necessitate sustainable management practices (Ayalew *et al.*, 2020; Alemneh, 2021; Dhyani *et al.*, 2022; Mengistu *et al.*, 2023).

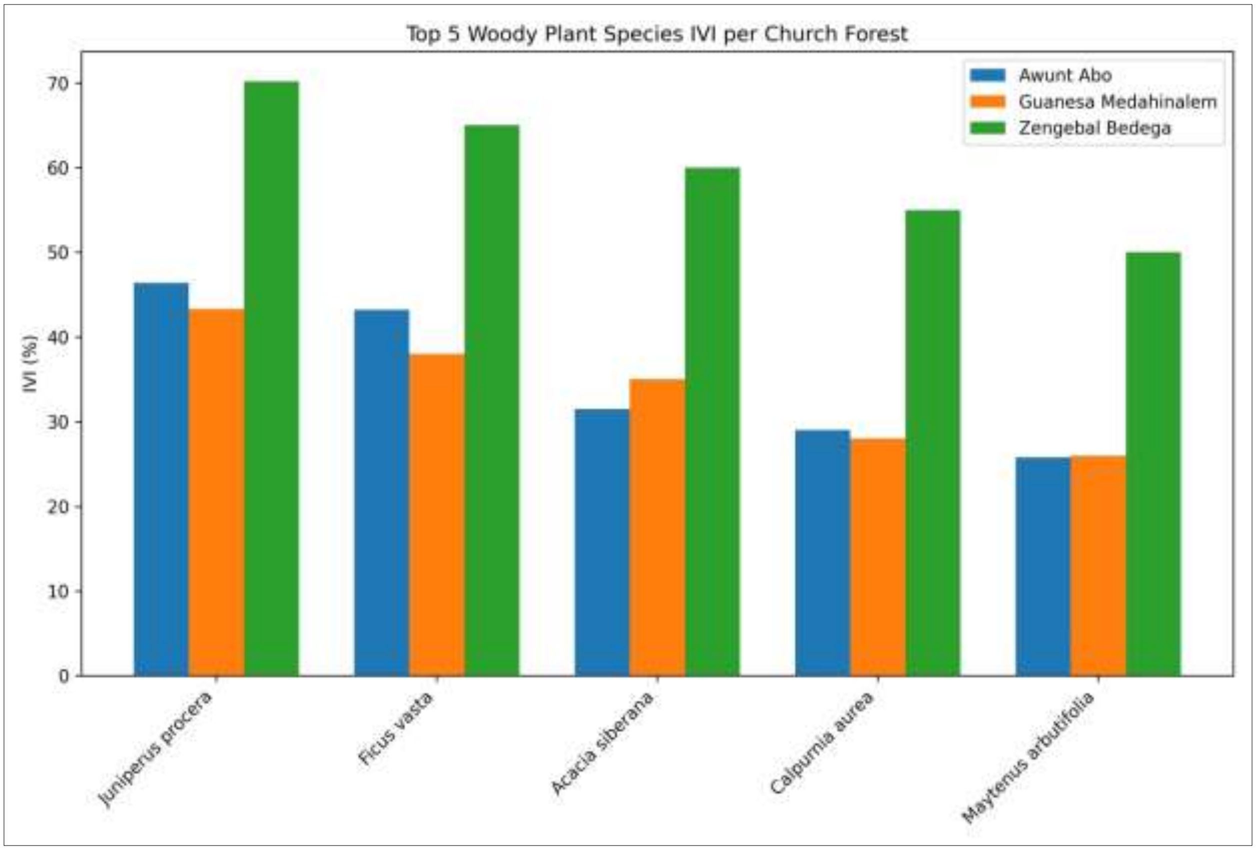
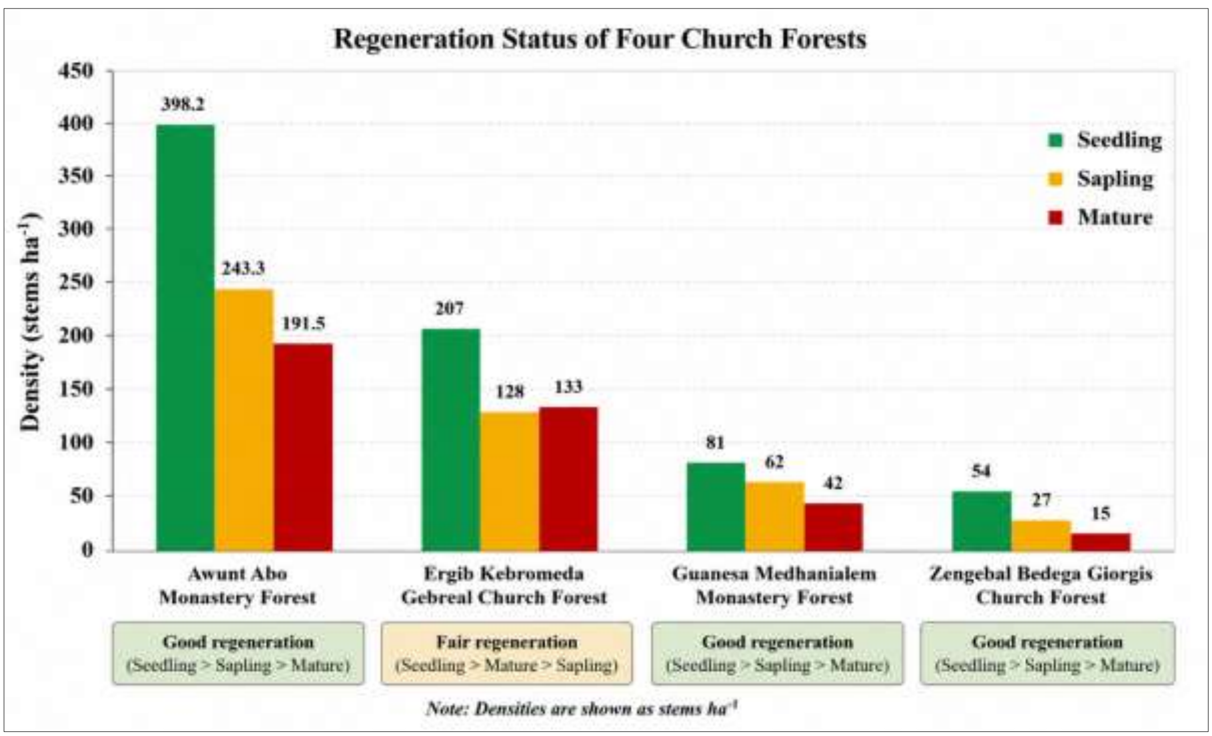


Figure 6. 2 Five top plant species for their IVI per the sampled church forests

6.4 Regeneration status of the woody plant Species

Awuntabo Monastry forests in semi-arid agro-ecology zone was 398.2, 243.3, and 191.5 stems ha−1 respectively for the density of seeding, sapling, and mature individuals of woody plants. Guanesa Medahinalem Monastry forest in sub-humid agro-ecology zone was 81, 62, and 42 for seedling, sapling, and mature individuals of woody plants, whereas the temperate-highland agro-ecology zone under Zengebal Bedega Giorgis church forest was 54, 27, and 15 for seedling, sapling, and mature individuals of woody plants respectively. Based on this result, and according to (Dhaulkhandi *et al.*, 2008), the regeneration status of the church forests of all church forests is fair regeneration since the density of seedlings > or ≤ saplings ≤ mature. The ratio of seedling to mature individuals of woody species in the forest was 0.61:1; the ratio of seedling to saplings was 0.78:1 and sapling to mature individuals was 0.47:1. According to (Tesfaye *et al.*, 2019) the results reveal a greater presence of seedlings than saplings and saplings than mature trees, indicating successful forest species regeneration.

Climatic factors and biotic interference influence the regeneration of various woody plant species in the forest (Supriatna, 2018). The lower density values of seedlings compared to saplings may be attributed to biotic disturbances and competition for space, light, and nutrient limitations (Uriarte et al., 2005). Data analysis suggests that the density values for seedlings and saplings in the forest's population structure are lower compared to mature individuals, deviating from typical population patterns (Mebrat, 2015; Birhanu *et al.*, 2021; Debebe *et al.*, 2023). This underscores the necessity of developing and implementing forest management strategies in the area to foster healthy regeneration and sustainable species use. The higher presence of sapling individuals compared to seedling individuals implies the progression of most seedlings to the sapling stage, likely due to the protected status of church forests within the community's religious practices (Mengistu *et al.*, 2023).



6. 3 Seedling and sapling distribution of woody species of sampling church forest

Among the three church forests under the three agro ecological zones Awuntabo Monastry has the highest seedling status within the semi-arid agro-ecological zone, whereas the lowest seedling status recorded Zengebal Bedega Giorgis church under temperate-highland agro-ecological zone (Figure 6.3). Guanesa Medahinalem Monastry has approximately near equal seedling and sapling status of the forests (Ahammad *et al.*, 2019). This scenario necessitates the implementation of conservation measures through prioritization (Ayalew *et al.*, 2020). To ensure this, the tree species in the three agro-ecological zones, from three church forests area were grouped into three regeneration status classes on the basis of their seedling and sapling densities per hectare (Table 6.2 up to 6.4). Species lacking both seedlings and saplings were categorized under class I; those with seedling and sapling densities ranging from one to fifteen were classified under class II, while the remaining species were assigned to class III.

Table 6. 2 List of tree species under regeneration status classes under semi-arid agro-ecological zone

Awuntabo Monastry		
I	II	III
Juniperus procera	*Albizia gummifera*	*Syzigium guineense*
Olea europaea	*Maytenus arbutifolia*	*Eucalvntus*
Ficus thonninii Blume	*Olea europaea*	*Carica papaya*
Ficus vasta	*Croton macrostachyus*	*Casuarina equisti*
Cordia Africana	*Erythrina abyssinica*	*Cofea Arabica*
Acacia siberana	*Phoenix sp*	*Euclea shchimperi*
Ficus sur	*Vernonia amygdalina*	*Mangifera indica*
Podocarpus falcatus	*Vernonia bipontinnii*	*Clutia lanceolata*
Millettia ferruginea	*Ximenia americana*	*Rosa abyssinica Lindley*
	Zizyphus spina- christi	*EchinopspappiiChiov*
	Scolopia theifolia	*Otostegiatomentosa*
	Rhus glutinosa Hochst	*Acacia nilotica*
	Rhus natalensis	*Adhatoda schimperiana*
	Pinus patula	*Bridelia micrantha*
	Pinus radiata	*Rumex nervosus*
	Podocarpus falcatus	*Buddleja polystachya*
	Millettia ferruginea	*Carissa spinarum*
	Myrica salicifolia	*Capans tomentosa*
	Myrsine africana	*Gnttiaf llginea*
	Mytenus undata	*Croton macrostachyus*
		Dodonia angustifolia
		Erythrina abyssinica
		Acacia polyacantha
		Maytenus arbutifolia

Table 6-3 List of tree species under regeneration status classes under sub-humid agro-ecology zone

Guanesa Medhanialem Monastry		
I	II	III
Ficus vasta *Olea europaea* *Juniperus procera* *Vernonia bipontinnii* *Scolopia theifolia* *Ficus thonninii Blume* *Acacia polyacantha* *Cordia Africana* *Allophyllus abyssinicus* *Vernonia bipontinnii* *Acacia siberana*	*Albizia gummifera* *Maytenus arbutifolia* *Olea europaea* *Croton macrostachyus* *Erythrina abyssinica* *Phoenix sp* *Vernonia amygdalina* *Ximenia americana* *Zizyphus spina- christi* *Scolopia theifolia* *Pinus radiata*	*Syzigium guineense* *Eucalvntus* *Carica papaya* *Casuarina equisti* *Cofea Arabica* *Euclea shchimperi* *Mangifera indica* *Clutia lanceolata* *Rosa abyssinica Lindley* *EchinopspappiiChiov* *Otostegiatomentosa* *Acacia nilotica* *Adhatoda schimperiana* *Bridelia micrantha* *Rumex nervosus* *Buddleja polystachya* *Carissa spinarum* *Capans tomentosa* *Gnttiaf llginea* *Croton macrostachyus* *Dodonia angustifolia* *Erythrina abyssinica* *Maytenus arbutifolia*

Table 6-4 List of tree species under regeneration status classes under temperate-highland agro-ecology zone

Zengebal Bedega Giorgis Church		
I	II	III
Juniperus procera *Ficus vasta* *Olea europaea* *Vernonia bipontinnii* *Scolopia theifolia* *Ficus thonninii Blume* *Cordia Africana* *Acacia abyssinica*	*Albizia gummifera* *Euphorbia abyssinica* *Buddleja polystachya* *Maytenus arbutifolia* *Ficus thonninii Blume*	*Erythrina abyssinica* *Dodonaea viscosa* *Calpurnia aurea* *Rumex nervosus*

6.5 Phyto- geographical Comparison among different agro-ecological zones

Comparing the similarity of species among different forests can provide a broad understanding of overall species richness, diversity, and phytogeographical similarity (Getaneh *et al.*, 2015). However, the comparison of species diversity between individual forests becomes challenging due to variations in factors such as size, survey methods, and study objectives (Birhanu *et al.*, 2021). Despite these challenges, assessing the overall species richness of a forest can still offer a general impression of its diversity and phytogeographical similarities.

In this context, the researcher conducted a comparison between three church forests in three different agro-ecological zones. The similarity indices between semi-arid, sub-humid, and temperate-highland agro-ecological zones ranged from 0.51 to 0.95. Specifically, the Sorenson's similarity index, which depends on the common species shared between compared forests, revealed that Awuntabo Monastery forest shared a significant number of species with reaching a high similarity index of 0.95, indicating a substantial similarity of church forests under semi-arid agroecological zone.

Awuntabo Monastery and Zengebal Bedega Giorgis church, both located in different agro-ecological zones, exhibited a lower similarity of 0.51. This disparity was attributed to anthropogenic factors causing disturbance in the latter church forest. Additionally, Awuntabo Monastery semi-arid and Guanesa Medahinalem Monastery under the sub-humid agro-ecological zone demonstrated a similarity index of 0.8, reflecting shared species. The high similarity between these church forests was attributed to similar forest management traditions, while differences were noted due to variations in altitude, distance between the church forests, and climatic factors.

6.6 Discussion

The present study revealed that church forests in Jabitehinan District harbour significant woody species diversity and structural variation, with *Fabaceae, Euphorbiaceae, Cupressaceae,* and *Oleaceae* emerging as dominant families across different agro-ecological zones. These findings align with previous research in northern and northwestern Ethiopia, which also documented high floristic richness in church forests due to their traditional protection by religious institutions (Wassie *et al.*, 2010). The Shannon-Wiener diversity values recorded in this study (ranging from 2.57 to 3.28) are higher than some reported in Weiramba forest (H' = 2.3) and comparable to Tara Gedam church forest (H' = 2.98) (Teshager *et al.*, 2018). This suggests that, despite increasing anthropogenic pressures, church forests continue to play a vital role as refuges for indigenous and ecologically significant species.

The structural analysis demonstrated that most individuals were concentrated in lower DBH and height classes, indicating strong regeneration but limited recruitment into larger tree categories. This trend reflects patterns reported in other community-managed forests in Ethiopia, where small to medium-sized individuals dominate due to selective harvesting of mature trees for fuel wood, timber, and construction (Mucheye *et al.*, 2020). While the dominance of seedlings and saplings indicates active regeneration, the limited presence of larger trees suggests possible long-term instability if mature individuals continue to be removed. Nonetheless, the presence of some dominant, large-sized individuals, particularly *Juniperus procera* and *Olea europaea*, demonstrates the potential for sustained carbon sequestration if protection is strengthened (Debebe *et al.*, 2023).

The regeneration analysis indicated a fair regeneration status across the studied church forests, with seedling density exceeding or equalling saplings, but both being lower than adults. This pattern, also reported in other Ethiopian church forests, suggests that regeneration is occurring but is not fully balanced (Tesfaye *et al.*, 2019). Biotic disturbances such as grazing, competition for light and nutrients, and human exploitation were likely contributing to reduced recruitment, consistent with findings from other forest ecosystems (Supriatna, 2018). However, the persistence of seedlings and saplings indicates that the cultural and religious protection of these forests continues to provide ecological benefits, even under increasing human pressure.

Phyto-geographical comparison revealed high similarity among church forests in semi-arid agro-ecological zones (Sorenson's index = 0.95), but lower similarity between forests in semi-arid and temperate highland zones (0.51). These variations are likely driven by differences in altitude, climatic conditions, and anthropogenic disturbance, as reported in similar ecological comparisons in Ethiopia (Getaneh *et al.*, 2015). The findings highlight the importance of conserving church forests across all agro-ecological zones to maintain genetic diversity and ecological connectivity. Furthermore, prioritizing conservation based on Importance Value Index (IVI) is critical, as species with low IVI scores face higher risks of local extinction (Ayalew *et al.*, 2020). Overall, this study underscores the ecological importance of church forests as biodiversity hotspots and emphasizes the need for integrated conservation measures to ensure their sustainability.

6.7 Policy Implications

The findings of this study have significant implications for forest management, biodiversity conservation, and climate change policy in Ethiopia. First, the high woody species diversity and the regeneration potential of church forests demonstrate that these sacred landscapes can serve as critical biodiversity reservoirs. Policymakers should therefore formally recognize church forests as integral components of the national conservation strategy, complementing state-protected areas. Integrating these forests into Ethiopia's Biodiversity Strategy and Action Plan would enhance long-term ecological resilience.

Second, the uneven regeneration and low representation of large-sized trees highlight the urgent need for stricter protection against anthropogenic pressures such as fuel wood collection, grazing, and selective logging. Policies should promote community-based forest management, empowering local religious leaders, congregations, and youth groups to participate in conservation while introducing incentives such as alternative energy sources and sustainable livelihood options to reduce dependence on forest resources.

Third, given the carbon sequestration potential of mature individuals such as *Juniperus procera* and *Olea europaea*, church forests should be integrated into national climate change mitigation frameworks, including REDD+ initiatives and Ethiopia's Climate Resilient Green Economy (CRGE) strategy. Such integration would not only support global climate goals but also provide financial resources for local forest protection through carbon credit schemes.

Finally, the ecological differences observed across agro-ecological zones suggest that conservation strategies should be site-specific, recognizing variations in species composition, structural dynamics, and disturbance levels. Policies should prioritize species with low Importance Value Index (IVI) through targeted enrichment planting and restoration programs. By linking cultural conservation traditions with formal policy frameworks, Ethiopia can strengthen the resilience of church forests as both spiritual sanctuaries and ecological strongholds.

6.8 Future Work

Although this study provides valuable insights into the woody species composition, structural patterns, and regeneration dynamics of church forests in the Jabitehinan District, further research is required to build a more comprehensive understanding by expanding spatial coverage through comparative studies across other districts and regions to examine how species composition and regeneration status vary under different socio-ecological contexts, while also establishing long-term ecological monitoring plots to capture temporal changes in forest structure, species diversity, and regeneration under ongoing anthropogenic and climatic pressures, in addition to investigating soil properties, hydrology, and microclimatic conditions that influence regeneration and distribution patterns within these unique forest ecosystems, alongside quantifying both aboveground and belowground biomass to strengthen evidence for the carbon sequestration potential of church forests in climate change mitigation and their possible integration into carbon trading initiatives.

Equally important is exploring socio-cultural dimensions to understand how traditional beliefs, cultural practices, and community participation contribute to forest conservation and resilience, while restoration ecology trials such as enrichment planting and assisted natural regeneration should be tested for species with low regeneration capacity or low Importance Value Index (IVI), and research should further assess the integration of church forests into Ethiopia's REDD+ initiatives and Climate Resilient Green Economy (CRGE) strategy by evaluating their economic benefits through carbon credits and ecosystem services, with future studies also extending beyond woody species to include non-woody flora, fauna, and pollinators so as to capture the broader ecological significance and ensure a holistic approach to church forest management and conservation.

6.9 Conclusion

The study conducted in Awunt Abo monastery, Ergib Kebromeda Gebreal church, Guanesa Medhanialem Monastry, and Zengebal Bedega Giorgis church forests revealed valuable insights into the woody plant diversity, distribution, and regeneration status. Here are the key conclusions drawn from the findings: The forests showed relatively high diversity and evenness of woody species. *Fabaceae, Asteraceae, Poaceae, Lamiaceae*, *Solanaceae,* and *Euphorbiaceae* were among the most diverse families. The most frequently distributed species varied among the sampled monasteries. Different forest areas were dominated by specific plant families, indicating heterogeneity in large plant distribution. Forests were dominated by small to medium-sized trees, suggesting anthropogenic activities such as selective cutting for charcoal, construction, and timber production. Height class distribution showed an inverted J-shape, indicating the impact of human activities on the forest structure. Larger-sized individuals dominated in church forests, particularly in Ergib Kebromeda Giorgis church forest. This dominance of larger-sized individuals is beneficial for carbon sequestration if well conserved. IVI varied among different woody plant species in the church forests, indicating the importance of certain species for conservation. Conservation priorities should be set based on IVI, with lower IVI species requiring high conservation efforts. Regeneration status was fair across all church forests, with successful seedling to sapling transition. Climatic factors and biotic interference influenced the regeneration of different woody plant species. Forest management regimes are needed to promote healthy regeneration and sustainable use of species. The Phyto-geographical comparison provides valuable information for understanding the distribution and similarity of plant species among different agro-ecological zones and church forests.

6.10 Recommendation

The recommendations for sustaining and enhancing the ecological, cultural, and economic value of church forests include strengthening legal protection by formally recognizing them as community conservation areas under regional forest proclamations and establishing legal frameworks to restrict deforestation, encroachment, and unsustainable resource use, while also promoting community-based management by empowering church leaders, congregations, and youth groups to co-manage forests and equipping them with training on forest monitoring, biodiversity documentation, and sustainable harvesting practices, along with introducing incentives for conservation through the promotion of alternative livelihoods such as beekeeping, ecotourism, and sustainable agriculture to reduce dependency on forest resources, complemented by expanded access to renewable energy technologies including solar, biogas, and improved stoves to minimize fuel wood reliance.

Furthermore, church forests should be integrated into national climate strategies by linking them with Ethiopia's Climate Resilient Green Economy (CRGE) and REDD+ programs to secure funding through carbon credits and promoting enrichment planting of carbon-dense native species such as *Juniperus procera* and *Olea europaea*, while site-specific restoration programs should prioritize species with low Importance Value Index (IVI) for targeted enrichment and adopt restoration approaches tailored to local agro-ecological conditions, supported by long-term research and monitoring of woody species diversity, regeneration dynamics, and carbon storage potential through collaborations between universities, research centers, and local churches, with parallel awareness and education initiatives that integrate church forest conservation into school curricula and community campaigns to emphasize their dual role as sacred sanctuaries and vital ecological strongholds.

Chapter Seven

Assessing the Carbon sequestration potential of church forest and their implication for climate change mitigation in Jabitehinan District, Ethiopia[2]

7.1 Introduction

Climate change involves a shift in global climate patterns, driven directly or indirectly by human activities that alter the atmosphere's composition, going beyond the natural variability observed over similar periods (IPCC, 2014b). Since 1990, human-caused greenhouse gas (GHG) emissions have increased by approximately 43% as of 2019 (IPCC, 2021), contributing to various climate-related impacts. The Earth's average surface temperature has risen by around 1.2°C since the late 19th century, with the majority of this warming occurring over the last 40 years (IPCC, 2014b). Climate change is marked by rising global temperatures, shifts in precipitation and cloud cover, melting ice caps, reduced snow cover, and increases in both ocean temperatures and acidity (UNFCCC, 2007b). These changes are primarily driven by the oceans' absorption of heat and carbon dioxide.

Developing countries face unique challenges due to climate change, including food insecurity, water scarcity, drought, disease spread, flood damage, and forced migration due to desertification or rising sea levels (UNDP, 2007b). Research indicates that greenhouse gas emissions have led to rapid, significant changes in Earth's climate, affecting temperature and precipitation patterns worldwide (IPCC, 2021). In recent years, recognition of the critical role forest ecosystems play in carbon sequestration has grown (IPCC, 2021). Nature-based solutions, particularly forest conservation, are increasingly valued for their potential to stabilize climate patterns, reduce natural disasters, and support biodiversity (Solomon, 2007; Dar *et al.*, 2019; IPCC, 2021). Forests act as crucial carbon reservoirs, with tropical and subtropical forests holding about two-thirds of global terrestrial carbon (Gatti *et al.*, 2021).

---

[2]Birhanie *et al* (2025) Assessing the carbon sequestration potential of church forest and their implication for climate change mitigation in Jabitehinan District, Ethiopia. Wily Geo: Geography and Environment 12(2), DOI: 10.1002/geo2.70026.

They store approximately 46% of the world's terrestrial carbon and around 11.55% of soil carbon (Maja *et al.*, 2021; Solomon, 2022; Lambert *et al.*, 2023). Forest nutrient cycling and uptake processes are also impacted by temperature, precipitation, and CO2 level changes (Girona *et al.*, 2023).

Effective climate change mitigation requires both mitigation and adaptation strategies. Forests play a substantial role by capturing atmospheric carbon dioxide through photosynthesis (Tadesse, 2008), making them vital in climate mitigation across various agro-climatic regions (Shahbazi *et al.*, 2016). The carbon sequestration potential of sacred forests, often maintained by local communities in developing nations, is increasingly recognized within comprehensive climate mitigation efforts (Bora *et al.*, 2013; Dar *et al.*, 2019). Sacred forests, as cultural conservation areas, exemplify effective approaches for addressing climate change (Daye *et al.*, 2015).

Despite forests' importance in carbon sequestration, tropical forests have experienced extensive deforestation, damaging ecosystems (FAO, 2015). In Ethiopia, significant deforestation especially of dry Afromontane forests has left only remnants in the highlands, primarily due to agricultural expansion, urbanization, and overgrazing (Lemenih *et al.*, 2008; Gobena, 2018; Gebeyehu *et al.*, 2019). This deforestation has led to biodiversity loss and reduced ecosystem services (Gebeyehu *et al.*, 2019). However, in northern Ethiopia, the Ethiopian Orthodox Tewahedo Church (EOTC) has been instrumental in preserving natural vegetation (Cardelús *et al.*, 2012; Maja *et al.*, 2021). Research has examined the ecological and conservation significance of church forests (Cardelús *et al.*, 2012; Tura *et al.*, 2013; Reynolds *et al.*, 2015; Endalew *et al.*, 2020; Birhanu *et al.*, 2021; Solomon, 2022).

However, the current study has several unique and original aspects. It is among the first to systematically assess the carbon sequestration potential of church forests in Jabitehinan District, thereby providing new data for a region that has often been underrepresented in previous carbon stock assessments. By examining church forests, which are culturally protected sacred sites; this study introduces a novel perspective that integrates ecology, spirituality, and climate science.

This expands the conventional understanding of forest conservation to include traditional and religious land stewardship practices (Aerts *et al.*, 2016). The use of a stratified systematic sampling method across three agroecological zones semi-arid, sub-humid, and temperate highland adds scientific rigour and a nuanced perspective to the study, enabling meaningful comparisons that are often lacking in similar research.

The integration of local and global perspectives demonstrates that local-level conservation initiatives significantly contribute to global climate change mitigation objectives, underscoring the value of decentralized approaches within broader climate policy frameworks (Agrawal *et al.*, 2008). Although limited, empirical studies have begun to provide quantitative evidence of the carbon storage potential of Ethiopian church forests, highlighting their critical role in biodiversity conservation and climate change mitigation (FAO, 2021).

Our research validates the environmental benefits of indigenous and community led conservation practices, offering potential models for REDD+ inclusion and climate financing. The study presents policy-relevant findings, showing that the statistically significant variation in carbon stock between agroecological zones offers actionable insights for region-specific forest management and climate policy planning in Ethiopia and similar landscapes.

This study aims to estimate carbon stock in church forests across three agro-ecological zones *Kolla* (Semi-arid), *Woyina Dega* (Sub-humid), and *Dega* (Temperate Highland) using non-destructive measurement techniques. It focuses on quantifying carbon stocks in above- and below-ground biomass, identified as potential carbon sink pools.

7.2 Data source and Sampling design

. This study employed a stratified random transect approach, selected for its ability to represent diverse land types, reduce variability, and offer flexibility (IPCC, 2006; FAO, 2015). Stratification was based on agro-ecological zones. A total of 10 transects were established, with one transect extending in each of the four cardinal directions from the church building within each forest, spaced 50 meters apart. The spacing between transect lines and plots was determined by considering vegetation density, spatial vegetation heterogeneity, and forest size, following guidelines by (Brown, 1997). To minimize edge effects, transects were positioned 100 meters from the edges of each forest. The first transect line was randomly established at the western edge of the forest, extending outward from the centre of the monastery.

Biomass data were collected from 60 sample plots across all church forests, with nested sampling quadrats measuring 15 x 15 m for large trees, 10 x 10 m for smaller trees, and 5 x 5 m for shrubs and grasses (Hairiah *et al.*, 2001; Pearson, 2007). These sampling units were placed at 50-meter intervals along transects. In the larger plots, tree diameters were measured at breast height (1.3 m) and stump height (30 cm) above ground level (Hairiah *et al.*, 2001; Pearson, 2007).

Forest carbon measurements can be carried out using either rectangular or circular plots. While both are commonly used, circular plots are advantageous for this study area due to ease of establishment and measurement, particularly in dense forests. They allow for more plots to be measured within a given area, enhancing statistical representativeness (Brown, 1997; Pearson, 2007)

7.3 Data Analysis

The carbon sequestration potential of church forests and its implications for climate change mitigation were assessed through aboveground and belowground biomass estimation. The estimation of aboveground biomass (AGB) in these forests is based on plot inventories and involves three primary steps. First, individual tree biomass was estimated using allometric biomass formulas. This data was then used to calculate plot-level biomass, which in turn was scaled up to provide an average per-hectare estimate (Houghton *et al.*, 2001a; Bonorino *et al.*, 2002; Chave *et al.*, 2005b).

Allometric equations in forest carbon measurement are mathematical relationships that link measurable tree attributes such as diameter at breast height (DBH), height, or volume to carbon stored in the biomass. These equations vary according to the study’s focus, the species involved, and data availability. Common types of allometric equations include the following:

Biomass Expansion Factor (BEF): These species-specific factors help estimate total AGB (including carbon) from variables like DBH or basal area (Chave *et al.*, 2005b). Volume-Based Equations: These equations calculate biomass and carbon content based on tree volume, which is derived from DBH and tree height measurements, and are particularly useful for irregularly shaped species (Bonorino *et al.*, 2002). Destructive Sampling Equations: In this method, researchers sample trees, harvest them, and directly measure biomass and carbon in components such as stems, branches, and leaves. This approach provides data for developing future carbon estimation models without further harvesting (Pearson, 2007). Component-Specific Equations: These equations target specific tree parts, such as stem biomass or foliage biomass, allowing for detailed carbon distribution assessments within the tree (Hairiah *et al.*, 2001). Species-Specific Equations: Tailored to individual tree species or groups, these equations account for variations in the relationships between a species' physical attributes and its carbon content (Houghton *et al.*, 2001a). Generic Equations: Generic or generalized equations apply across multiple species when specific data is unavailable, making them useful for large-scale assessments (Yang *et al.*, 2009). Regional or Local Equations: Developed at regional or local levels, these equations account for variations in growth patterns, climate, and other factors that affect carbon content (Tura *et al.*, 2013).

In this study, non-destructive stand-level allometric equations were chosen, as forest preservation in monasteries restricts tree cutting. The researchers used non-destructive stand-level allometric equations, as these methods provide accurate estimates of biomass without causing damage to the forest structure (Chave *et al.*, 2005b). This approach is particularly important in ecologically and culturally sensitive areas like Ethiopian church forests, where preserving the integrity of both the ecosystem and the cultural heritage is essential (Kindu *et al.*, 2022). These forests hold profound spiritual significance for followers of the Ethiopian Orthodox Tewahido Church, who view them as sacred spaces inhabited by angels and saintly monks (EFCCC, 2018).

As a result, destructive sampling methods are strictly prohibited. Therefore, non-destructive techniques are the most appropriate and respectful option for biomass assessment in these settings.

These equations were effective for estimating carbon stocks at the stand level without causing forest disturbance (PicardSaint-Andre *et al.*, 2012). The equations developed by the Woody Biomass Inventory and Strategic Planning Project for all woody species across various agro-ecological zones in Ethiopia were used to calculate tree carbon stock, which was later compared with our estimated results (Parent, 2000).

AGB = (1.4277*DBH) + (0.0088*(DBH exp 3.0)) …....Equation (1)

Where AGB represents the Above Ground Biomass (kg/tree), and

DBH = Diameter of Brest Height (cm)

Tree biomass were converted to carbon stock (Hairiah *et al.*, 2001; Pearson, 2007)

AGB Carbon Stock = Above Ground Biomass * 0.5 …………………….....Equation (2)

Where, AGB = Above Ground Biomass (kg/tree)

Belowground carbon stock was calculated using the following approach:

Determining the most suitable root-to-shoot ratio (RSR) for dry Afro-mountain plant species requires an understanding of the specific ecological needs of these plants. Although RSR values of 0.2 and 0.25 are both applicable, empirical studies and ecological principles can help guide the selection (FAO, 2018). Soils in mountainous areas are often nutrient-poor and rocky, and a higher RSR (such as 0.25) implies a more extensive root system, enabling plants to explore a larger soil volume for nutrients (Lambers, 2008). In dry Afro-mountain regions, plants need to maximize water uptake and minimize water loss. A higher RSR reflects greater investment in root biomass, essential for accessing deeper soil moisture. Research indicates that plants with higher root biomass are better adapted to drought conditions (Comas *et al.*, 2013).

Thus, root biomass is often estimated from the root-to-shoot ratio by calculating 25% of the aboveground biomass to estimate root biomass (Hairiah *et al.*, 2001; Pearson, 2007; Yang *et al.*, 2009; PicardSaint-Andre *et al.*, 2012).

Root Biomass = AGB x 0.25 …………………………………Equation (3)

Where, AGB = Above Ground Biomass (kg/tree)

Trees, like other plants, are primarily composed of organic materials, with carbon being a significant component that constitutes approximately 50% of the dry weight of biomass (Brown, 1997). This high carbon content arises from the molecular structure of key biochemical components in plant tissues, including cellulose, hemicellulose, and lignin, all of which contain carbon as a fundamental element. The guidelines set by the Intergovernmental Panel on Climate Change (IPCC, 2006) and various forestry and ecological research methodologies recommend using a conversion factor of 0.5 to estimate carbon stock from biomass. Consequently, tree biomass is converted to carbon stock by applying this 0.5 factor (Hairiah *et al.*, 2001; Pearson, 2007; Lehtonen *et al.*, 2020).

AGBCS = Above Ground Biomass * 0.5 …………………………Equation (4)

Where, AGBCS = Above Ground Biomass Carbon Stock (kg/tree)

The total carbon stock density was calculated by summing all the carbon pool stock densities using the following formula:

C Density = CAGTB + CBGTB ………………...Equation (5)

Where, C Density = Carbon Stock Density (Mg ha^{-1})

CAGTB = Carbon Stock in Above Ground Tree Biomass (Mg ha^{-1})

CBGB = Carbon Stock in Below Ground Tree Biomass (Mg ha^{-1})

The total carbon stock was converted to carbon dioxide equivalent (CO_2 equivalent) by taking into account the molecular weight ratio of carbon dioxide to carbon. The molecular weight of CO_2 is 44.01 g/mol, while that of carbon (C) is 12.01 g/mol (Pearson, 2007).

The conversion factor is CO_2 equivalent= Carbon Stock×44.01/12.01≈3.67

7.3.1 Statistical analysis

Initially, the data were examined to confirm normal distribution and homogeneity of variance before proceeding with subsequent parametric statistical analyses. The independent variables were categorized as habitat types, while aboveground biomass, belowground biomass, and carbon density were defined as dependent variables. Using SPSS (version 20), a one-way ANOVA followed by Tukey's Post-Hoc test was performed to compare aboveground biomass, belowground biomass, and carbon density across the three agro-ecological zones. Statistical significance was set at the $p < .05$ level, with distinct letters assigned to the means indicating significant differences.

7.4 Result and Discussion

7.4.1 Forest carbon stocks from Semi-arid Agro-ecological Zone

The results indicated that the mean values for aboveground biomass, belowground biomass, aboveground carbon stock, belowground carbon stock, and total carbon stock were 258.6 $Mg.ha^{-1}$, 64.9 $Mg.ha^{-1}$, 76.6 $ton.ha^{-1}$ (equivalent to 280.3 $ton.ha^{-1}$), 19.2 $ton.ha^{-1}$ (equivalent to 70.4 $ton.ha^{-1}$), and 95.8 $ton.ha^{-1}$ (equivalent to 351.58 $ton.ha^{-1}$), respectively (Table 7-1). The minimum and maximum aboveground carbon stocks were estimated at 0.0001 $ton.ha^{-1}$ and 917.93 $ton.ha^{-1}$, respectively, while the minimum and maximum belowground carbon stocks were 0.0001 $ton.ha^{-1}$ and 229.4 $ton.ha^{-1}$, respectively.

Table 7-1 Above Ground Biomass (AGB), Below Ground Biomass (BGB), Above Ground Carbon Stock (AGCS), Below Ground Carbon Stock (BGCS), and Total Carbon (TC) for in Semi-arid agro-ecological zone

Agro-Ecological Zone	Church	AGB ($Mg.ha^{-1}$)	BGB ($Mg.ha^{-1}$)	AGBCS ($ton.ha^{-1}$)	BGBCS ($ton.ha^{-1}$)	TC ($ton.ha^{-1}$)	$CO_{2equivalant}$ ($tonCO_2eq.ha^{-1}$)
Semi-arid	Awuntabo Monastry	258.6	64.9	76.6	19.2	95.8	351.58

In the semi-arid agro-ecological zone, the top ten species with the highest carbon concentrations included *Eucalyptus camaldulensis* with 730.02 $ton.ha^{-1}$ (equivalent to 2679.1 $tonCO_2eq.ha^{-1}$)), *Acacia abyssinica* with 240.18 $ton.ha^{-1}$ (881.49 $tonCO_2eq.ha^{-1}$)), *Acacia polyacantha* with 180.50 $ton.ha^{-1}$ (662.44 $tonCO_2eq.ha^{-1}$)), *Olea europaea* with 170.55 $ton.ha^{-1}$ (625.92 $tonCO_2eq.ha^{-1}$)), *Syzygium guineense* with 151.75 $ton.ha^{-1}$ (556.92 $tonCO_2eq.ha^{-1}$)), *Euphorbia tirucalli* with 51.11 $ton.ha^{-1}$ (187.57 tons of CO_2), and *Acacia nilotica* with 18.58 $ton.ha^{-1}$ (68.19 $tonCO_2eq.ha^{-1}$)). Conversely, the species contributing the least to carbon sequestration were *Acokanthera schimperi* (5.18 $ton.ha^{-1}$, 19.03 tons of CO_2), *Rumex nervosus* (0.0014 $ton.ha^{-1}$, 0.005 $tonCO_2eq.ha^{-1}$)), and *Acacia siberiana* (0.0013 $ton.ha^{-1}$, 0.004 $tonCO_2eq.ha^{-1}$) (Table 5-2).

The percentage contributions for each species were as follows: *Eucalyptus camaldulensis* (47.16%), *Acacia abyssinica* (15.51%), *Acacia polyacantha* (11.66%), *Olea europaea* (11.01%), *Syzygium guineense* (9.80%), *Rumex nervosus* (9.07%), *Acacia siberiana* (8.79%), *Euphorbia tirucalli* (3.30%), Acacia nilotica (1.20%), and *Acokanthera schimperi* (0.33%) of the total species in the agro-ecological zone.

Among the top ten species recorded in the semi-arid agro-ecological zone, *Eucalyptus camaldulensis Dehnh* was the most significant contributor to climate mitigation, sequestering 730.02 $ton.ha^{-1}$ (equivalent to 2679.1 $tonCO_2eq.ha^{-1}$) (Table 7-2). This figure surpasses the findings of Bazezew *et al.* (2015) regarding carbon stock in the Adaba-Dodola community forest. The variation may be attributed to the high conservation status, age, and larger diameter of the trees in the sacred forest examined in the current study.

In the *kolla* (semi-arid) agro-ecological zone, previous studies have reported varying results: Gujube (2015) found aboveground carbon at 1171.17 $ton.ha^{-1}$ and belowground carbon at 55.42 $ton.ha^{-1}$; Girma *et al.* (2014) reported aboveground carbon at 471.1 tons/ha and belowground carbon at 83.42 tons/ha; and Aregie *et al.* (2019) recorded aboveground carbon at 34.73 $ton.ha^{-1}$ and belowground carbon at 9.01 $ton.ha^{-1}$. In contrast, the current study revealed mean values of 76.6 $ton.ha^{-1}$for aboveground carbon and 19.2 $ton.ha^{-1}$for belowground carbon, which are lower than previous studies within the same agro-ecological zone, except for the Sekele-Mariam dry evergreen mountain forest studied by Mekonnen *et al.* (2019), which reported aboveground carbon stock at 37.54 $ton.ha^{-1}$and belowground carbon stock at 9.76 $ton.ha^{-1}$.

The observed variations in carbon levels in aboveground and belowground biomass can be attributed to factors such as intensive forest degradation, differences in stand structure and composition, topography, altitude, and variations in microclimate.

Table 7-2 Above Ground Biomass (AGB), Below Ground Biomass (BGB), Above Ground Carbon Stock (AGCS), Below Ground Carbon Stock (BGCS), and Total Carbon (TC) for ten top species in Semi-arid agro-ecological zone

Scientific Name	AGB($Mg.ha^{-1}$)	BGB($Mg.ha^{-1}$)	AGCS ($ton.ha^{-1}$)	BGCS ($ton.ha^{-1}$)	TC ($ton.ha^{-1}$)	$CO_{2equivalant}$ ($tonCO_2eq.ha^{-1}$)
Acokanthera schimperi	8295.56	4147.782	4.14	1.03	5.18	19.03
Olea europaea	272888.80	68222.19	136.44	34.11	170.55	625.92
Acacia nilotica	29731.41	7432.85	14.86	3.71	18.58	68.19
Rumex nervosus	3.23	0.80	0.00	0.00	0.00	0.05
Acacia abyssinica	384307.60	96076.90	192.15	48.03	240.18	881.49
Syzigium guineense	242814.90	60703.73	121.40	30.35	151.75	556.92
Eucalyptus camaldulensis Dehnh.	1168057	292014.20	584.02	146.00	730.02	2679.19
Acacia siberana	0.28	0.07	0.00	3.57	0.00	0.04
Acacia polyacantha	288815.30	72203.82	144.4	36.10	180.50	662.44
Euphorbia tirucalli	81796.62	20449.15	40.89	10.22	51.11	187.57

7.4.2 Forest Carbon Stocks in the Sub-Humid Agro-Ecological Zone

The calculated mean values for aboveground biomass, belowground biomass, aboveground carbon stock, belowground carbon stock, and total carbon for the Sub-humid agro-ecological zone were 50.4 $Mg.ha^{-1}$, 12.9 $Mg\ ha^{-1}$, 12.4 $ton.ha^{-1}$ (equivalent to 45.14 $tonCO_2eq.ha^{-1}$), 3.1 $ton.ha^{-1}$ (equivalent to 11.37 $tonCO_2eq.ha^{-1}$), and 15.5 $ton.ha^{-1}$ (equivalent to 56.88 $tonCO_2eq.ha^{-1}$), respectively (Table 7-3). The estimated minimum and maximum values for aboveground carbon stock ranged from 0.0001 $ton.ha^{-1}$ to 164.1 $ton.ha^{-1}$. For belowground carbon stock, the minimum and maximum values were 0.001 $ton.ha^{-1}$ and 32.8 $ton.ha^{-1}$, respectively.

Table 7-3 Above Ground Biomass (AGB), Below Ground Biomass (BGB), Above Ground Carbon Stock (AGCS), Below Ground Carbon Stock (BGCS), and Total Carbon (TC) for in Sub-humid agro-ecological zone

Agro-Ecological Zone	Church	AGB ($Mg.ha^{-1}$)	BGB ($Mg.ha^{-1}$)	AGBCS ($ton.ha^{-1}$)	BGBCS ($ton.ha^{-1}$)	TC ($ton.ha^{-1}$)	$CO_{2equivalant}$ ($tonCO_2eq.ha^{-1}$)
Sub-Humid	Guanesa Medhanialem	50.4	12.9	12.4	3.1	15.5	56.88

The top ten species with the highest carbon concentrations in the Sub-humid agro-ecological zone included *Ficus vasta* (156.32 $ton.ha^{-1}$, equivalent to 573.7 $tonCO_2eq.ha^{-1}$), *Dombeya torrida* (44.17 $ton.ha^{-1}$, equivalent to 162.13 $tonCO_2eq.ha^{-1}$), *Erica arborea* (37.89 $ton.ha^{-1}$, equivalent to 139.07 $tonCO_2eq.ha^{-1}$), *Juniperus procera* (32.23 $ton.ha^{-1}$, equivalent to 118.03 $tonCO_2eq.ha^{-1}$), *Ekebergia capensis* (27.65 $ton.ha^{-1}$, equivalent to 101.48 $tonCO_2eq.ha^{-1}$), *Vernonia bipontinnii* (18.69 $ton.ha^{-1}$, equivalent to 68.61 $tonCO_2eq.ha^{-1}$), and *Vernonia amygdalina* (7.41 $ton.ha^{-1}$, equivalent to 27.22 $tonCO_2eq.ha^{-1}$). The species with the lowest contributions were *Croton macrostachyus* (2.47 $ton.ha^{-1}$, equivalent to 9.08 $tonCO_2eq.ha^{-1}$), *Albizia gummifera* (0.38 $ton.ha^{-1}$, equivalent to 1.40 $tonCO_2eq.ha^{-1}$), and *Cordia africana* (0.28 $ton.ha^{-1}$, equivalent to 1.04 $tonCO_2eq.ha^{-1}$) (Table 7-4).

The percentage contributions for each species were as follows: *Ficus vasta* (47.72%), *Dombeya torrida* (13.48%), *Erica arborea* (11.56%), *Juniperus procera* (9.84%), *Ekebergia capensis* (8.44%), *Vernonia bipontinnii* (5.70%), and *Vernonia amygdalina* (2.26%) were the highest contributors to carbon sequestration. In contrast, *Croton macrostachyus* (0.75%), *Albizia gummifera* (0.11%), and *Cordia africana* (0.08%) had the lowest contributions.

Among the top ten species recorded in the Sub-humid agro-ecological zone, *Ficus vasta* (156.32 $ton.ha^{-1}$, equivalent to 573.7 $tonCO_2eq.ha^{-1}$) made the most significant contribution to climate mitigation (Table 4). Previous studies in the Sub-humid agro-ecological zone reported varying carbon stock levels: Dereje *et al.* (2022) found an aboveground carbon stock of 58.76 $ton.ha^{-1}$ and belowground carbon stock of 32.51 $ton.ha^{-1}$ in Montogera Estifanos Church Forest; Mekonnen *et al.* (2019) reported aboveground and belowground carbon stocks of 28.96 tons/ha and 7.52

ton.ha⁻¹, respectively; and Chinasho *et al.* (2015) found aboveground and belowground carbon stocks of 140.57 ton.ha⁻¹ and 66.07 ton.ha⁻¹, respectively.

In contrast, the present study found mean aboveground and belowground carbon stocks of 12.1 ton.ha⁻¹ and 3.1 ton.ha⁻¹, respectively, which are lower than those reported in previous studies within the same agro-ecological zone. This variation may be attributed to the lower average tree diameters in the church forests studied, the dominance of burial walls in the church, and significant disturbances to the sacred forest from their own cattle interference within the monasteries.

Table 7-4 Above Ground Biomass (AGB), Below Ground Biomass (BGB), Above Ground Carbon Stock (AGCS), Below Ground Carbon Stock (BGCS), and Total Carbon (TC) for top ten species under Sub-Tropical agro-ecological zone

Scientific Name	AGB(Mg.ha⁻¹)	BGB(Mg.ha⁻¹)	AGCS (ton.ha⁻¹)	BGCS (ton.ha⁻¹)	TC (ton.ha⁻¹)	$CO_{2equivalent}$ ($tonCO_2eq.ha^{-1}$)
Juniperus procera	51578.59	12894.65	25.78	6.44	32.23	118.03
Croton macrostachyus	3962.34	990.58	1.98	0.49	2.47	9.08
Ficus vasta	250114.50	62528.64	125.05	31.26	156.32	573.70
Cordia africana	455.72	113.93	0.22	0.05	0.28	1.04
Dombeya torrida	70685.54	17671.39	35.34	8.83	44.17	162.13
Ekebergia capensis Sparrm.	44245.99	11061.50	22.12	5.53	27.65	101.48
Erica arborea L.	60630.46	15157.62	30.31	7.578	37.89	139.07
Vernonia amygdalina	11869.85	2967.46	5.93	1.48	7.41	27.22
Albizia gummifera	3819.57	0.47	1.90	0.38	0.38	1.40
Vernonia bipontinnii	29914.16	7478.53	14.95	3.73	18.69	68.61

7.4.3 Forest carbon stocks from Temperate Highland Agro-ecological zone

The calculated mean values for aboveground biomass, belowground biomass, aboveground carbon stock, belowground carbon stock, and total carbon in the temperate highland agro-ecological zone were 71.2 Mg.ha⁻¹, 17.8 Mg.ha⁻¹, 11.2 ton.ha⁻¹ (equivalent to 40.73 $tonCO_2eq.ha^{-1}$), 2.8 ton.ha⁻¹ (equivalent to 10.27 $tonCO_2eq.ha^{-1}$), and 14.01 ton.ha⁻¹ (equivalent to 51.01 $tonCO_2eq.ha^{-1}$), respectively (Table 7-5). The estimated minimum and maximum values for aboveground carbon density ranged from 0.004 ton.ha⁻¹ to 91.7 tons/ha, while the minimum and maximum values for belowground carbon density were 0.001 $ton.ha^{-1}$ and 22.92 $ton.ha^{-1}$, respectively.

Table 7-5 :- Above Ground Biomass (AGB), Below Ground Biomass (BGB), Above Ground Carbon Stock (AGCS), Below Ground Carbon Stock (BGCS), and Total Carbon (TC) for in temperate-highland agro-ecological zone

Agro-Ecological Zone	Church	AGB ($Mg.ha^{-1}$)	BGB ($Mg.ha^{-1}$)	AGBCS ($ton.ha^{-1}$)	BGBCS ($ton.ha^{-1}$)	TC ($ton.ha^{-1}$)	$CO_{2equivalent}$ ($tonCO_2eq.ha^{-1}$)
Temperate Highland	Zengebal Bedega	71.2	17.8	11.2	2.8	14.01	51.41

The top ten species with the highest carbon concentrations in the temperate highland agro-ecological zone included *Erythrina abyssinica* (114.62 $ton.ha^{-1}$, equivalent to 420.68 $tonCO_2eq.ha^{-1}$), *Lobelia rhynchopetalum* (36.03 $ton.ha^{-1}$, equivalent to 133.24 $tonCO_2eq.ha^{-1}$), *Ficus vasta* (31.96 $ton.ha^{-1}$, equivalent to 117.32 $tonCO_2eq.ha^{-1}$), *Dodonaea viscosa* (7.69 $ton.ha^{-1}$, equivalent to 28.25 $tonCO_2eq.ha^{-1}$), *Olea europaea* (2.04 $ton.ha^{-1}$, equivalent to 7.48 $tonCO_2eq.ha^{-1}$), and *Podocarpus falcatus* (1.94 $ton.ha^{-1}$, equivalent to 7.15 $tonCO_2eq.ha^{-1}$). Conversely, the species with the lowest contributions were *Hagenia abyssinica* (0.38 $ton.ha^{-1}$, equivalent to 1.42 $tonCO_2eq.ha^{-1}$), *Aningeria adolfi-friedericii* (0.10 $ton.ha^{-1}$, equivalent to 0.40 $tonCO_2eq.ha^{-1}$), *Allophyllus abyssinicus* (0.05 $ton.ha^{-1}$, equivalent to 0.19 $tonCO_2eq.ha^{-1}$), and *Erica arborea* (0.05 tons/ha, equivalent to 0.20 $tonCO_2eq.ha^{-1}$) (Table 7-6).

The percentage contributions for each species were as follows: *Erythrina abyssinica* (58.72%), *Lobelia rhynchopetalum* (18.59%), *Ficus vasta* (16.37%), *Dodonaea viscosa* (3.94%), *Olea europaea* (1.04%), and *Podocarpus falcatus* (0.99%) were the highest contributors to carbon sequestration. In contrast, *Hagenia abyssinica* (0.19%), *Aningeria adolfi-friedericii* (0.05%), *Allophyllus abyssinicus* (0.02%), and *Erica arborea* (0.02%) had the lowest contributions.

Among the top ten species recorded in the temperate highland agro-ecological zone, *Erythrina abyssinica* (114.62 tons/ha, equivalent to 420.68 $tonCO_2eq.ha^{-1}$) made the most significant contribution to climate mitigation (Table 7-6). Previous studies in this agro-ecological zone have reported varying carbon stock levels: Girma *et al.* (2014) found aboveground and belowground carbon stocks of 471.1 $ton.ha^{-1}$ and 83.42 $ton.ha^{-1}$, respectively; Tura *et al.* (2013) reported aboveground and belowground carbon stocks of 42.40 $ton.ha^{-1}$ and 11.02 $ton.ha^{-1}$; and Dereje *et al.* (2022) found aboveground and belowground carbon stocks of 6.00 $ton.ha^{-1}$and 1.47 $ton.ha^{-1}$, respectively.

In comparison, the present study found mean aboveground and belowground carbon stocks of 11.2 $ton.ha^{-1}$ and 2.8 $ton.ha^{-1}$, respectively, which are lower than those reported in previous studies, except for the Mai-Anbesa Kidane Miheret Monastery Forest studied by Dereje *et al.* (2022) within the same agro-ecological zone. The disparity in carbon stock at the church forest site is likely attributed to differences in tree age, forest management practices, the allometric model employed, regional variations in soil and topography, as well as the height and diameter at breast height (DBH) of the trees.

Table 7-6 Above Ground Biomass (AGB), Below Ground Biomass (BGB), Above Ground Carbon Stock (AGCS), Below Ground Carbon Stock (BGCS), and Total Carbon (TC) for top ten species under temperate highland agro-ecological zone

Scientific Name	AGB($Mg.ha^{-1}$)	BGB($Mg.ha^{-1}$)	AGCS ($ton.ha^{-1}$)	BGCS ($ton.ha^{-1}$)	TC ($ton.ha^{-1}$)	$CO_{2equivalent}$ ($tonCO_2eq.h^{-1}$)
Lobelia rhynchopetalum	58089.79	14522.45	29.04	7.26	36.30	133.24
Podocarpus falcatus	3118.33	779.58	1.55	0.38	1.94	7.15
Hagenia abyssinia	620.30	155.07	0.31	0.07	0.38	1.42
Olea europaea	3261.10	815.27	1.63	0.40	2.03	7.48
Ficus vasta	51151.38	12787.84	25.57	6.39	31.96	117.32
Aningeria adolfi-friedericii	175.10	43.77	0.08	0.02	0.10	0.40
Erythrina abyssinica	183405.10	45851.28	91.70	22.92	114.62	420.68
Allophyllus abyssinicus	85.47	21.36	0.04	0.01	0.053	0.19
Erica arborea L.	87.43	21.85	0.04	0.01	0.05	0.20
Dodonaea viscosa	11.7	30.79	15.39	0.01	7.69	28.25

Among the top thirty species identified across the three agro-ecological zones, the three highest total carbon sequesters *Eucalyptus camaldulensis Dehnh.*, *Acacia abyssinica*, and *Acacia polyacantha* (Table 7-2) were found in the semi-arid agro ecological zone. This higher carbon sequestration can be attributed to lower disturbance rates, greater diameter at breast height, efficient water use, religious respect for the trees, and the absence of burial constructions with in the Monastry.

In terms of carbon sequestration potential, the semi-arid zone exhibited the highest capacity, followed by the sub-humid zone, while the temperate highland zone had the lowest potential (Table 7-7 and Figure 7:1).

Table 7-7 Total carbon stock (ton.ha^{-1}) across different agro-ecological zones

Agro-Ecological Zone	Semi-Arid zone	Sub-Tropical zone	Temperate Highland zone
Total Carbon Stock (ton.ha-1)	95.8	15.5	14.01

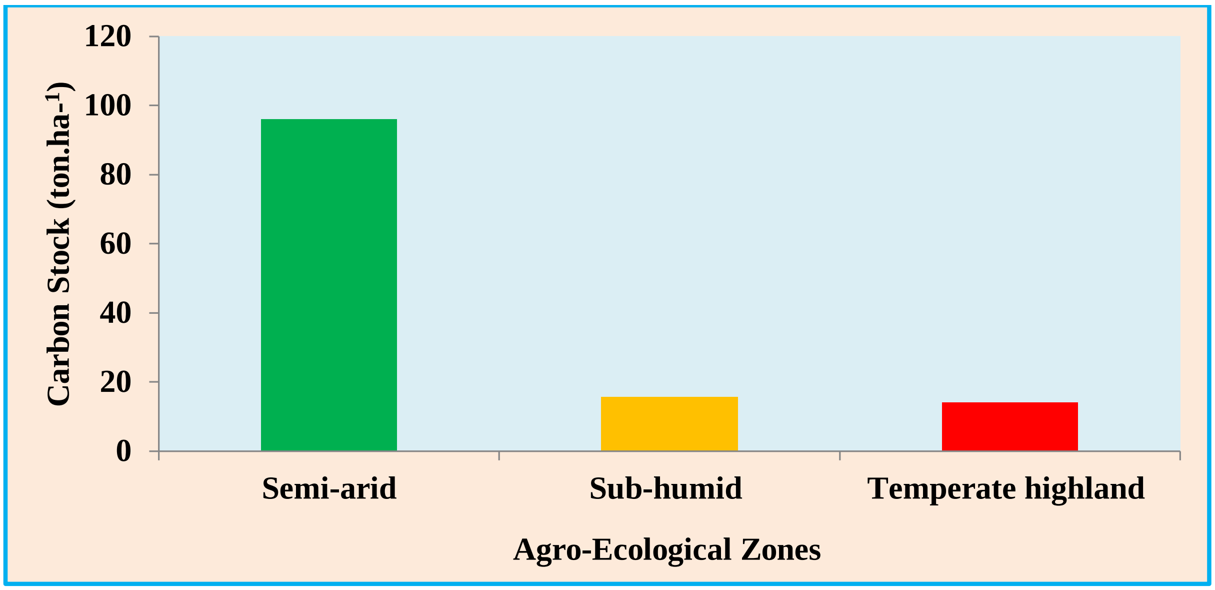


Figure 7. 1 Carbon stock density (ton.ha^{-1}) across different agro-ecologies

Among the three agro-ecological zones, five top species were identified for their carbon stocking potential. *Eucalyptus camaldulensis Dehnh* 730.02 ton.ha^{-1} had the highest potential followed by *Acacia abyssinica* 240.18 ton.ha^{-1}, *Acacia Polyacantha* 180.50 ton.ha^{-1}, *Olea europea* 170.55 ton.ha^{-1} and *Ficus vasta* 156.32 ton.ha^{-1} (Table 7-8 and figure 7:2).

Table 7-8 Carbon stock density (ton.ha^{-1}) of five major tree species across agro-ecologies

Species Name	Agro ecology	Carbon stock (ton.ha^{-1})
Eucalyptus camaldulensis Dehnh.	Semi-Arid	730.02
Acacia abyssinica	Semi-Arid	240.18
Acacia Polyacantha	Semi- Arid	180.50
Olea europea	Semi-Arid	170.55
Ficus vasta	Sub-Tropical	156.32

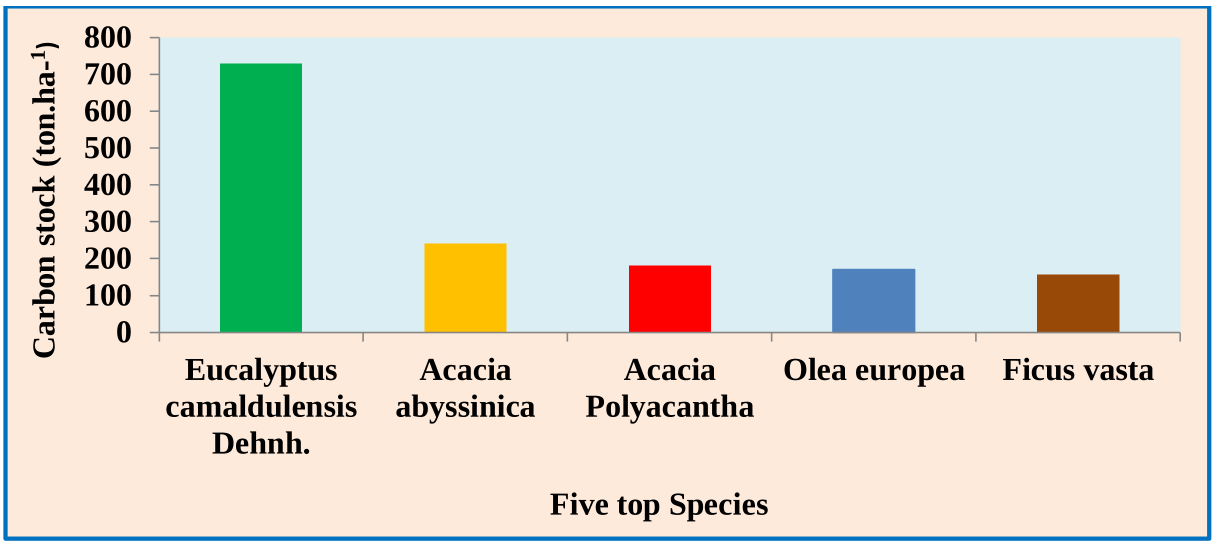


Figure 7. 2 Five top species carbon density from the three agro-ecological zones

The study examined the distribution of carbon stocks in various pools, including aboveground and belowground tree carbon, across the different agro-ecological zones. The findings indicated a statistically significant variation in carbon stock among these pools across the agro-ecological zones (Table 7-9). Additionally, the analysis of variance showed a significant difference in carbon stock among the various pools at different sites (p-value = 0.033) (Table 7-9). The Post-Hoc Tukey’s test revealed significant differences in aboveground and belowground carbon pools between the semi-arid zone and the sub-humid zone (p-value = 0.044), while no significant difference was observed between the temperate highland zone and the other zones in this study (Table 7-10).

Table 7-9 Analysis of variance (ANOVA) for carbon stock among different agro-ecological zones

Source of Variation	df	Mean Square	F-value	Significance (p-value)
Between Groups	2	85444.477	3.540	.033
Within Groups	102	24135.698		
Total	104			

Table 7-10 Post-Hoc Pairwise Comparison of aboveground biomass, belowground biomass, and carbon density among the three agro-ecological zones

(I) Agro-ecological zone	**(J) Agro-ecological zone**	**Mean Difference (ton.ha^{-1})**	**Standard Error**	**Significance (p-value)**
Sub-humid	Semi-arid	80.404*	33.105	0.044
Sub-humid	Temperate highland	81.992	44.733	0.164
Semi-arid	Sub-humid	-80.404*	33.105	0.044
Semi-arid	Temperate highland	1.588	45.955	0.999
Temperate highland	Sub-humid	-81.992	44.733	0.164
Temperate highland	Semi-arid	-1.588	45.955	0.999

*Significant at $\alpha = 0.05$ (95% confidence level).

7.5 Discussion

7.5.1 Forest management practices of the Ethiopian Orthodox Tewahido Church

In the northern highlands of Ethiopia, fragmented remnants of ancient Afromontane forests are preserved exclusively around the Ethiopian Orthodox Tewahedo Churches (Bongers *et al.*, 2006). The Ethiopian Orthodox Church is one of the oldest Christian institutions in the world (Mulat, 2013). Since the introduction of Christianity, the church has been managing its surrounding environment based on its religious principles and justifications (Wassie *et al.*, 2006b). The theological foundation and religious perspective of the Ethiopian Orthodox Tewahedo Church in conserving forest resources are deeply rooted in the teachings of the Holy Scriptures (Bongers *et al.*, 2006). The Ethiopian Orthodox Tewahedo Church emphasizes a philosophy of nature conservation that integrates the protection, sustainable utilization, and development of forest resources (Wassie *et al.*, 2010). The Ethiopian Orthodox Tewahedo Church has a long-standing tradition of planting and conserving tree species. Church compounds serve as sanctuaries for trees and other biodiversity, preserving species that might have otherwise been lost (Tilahun *et al.*, 2015b). Many indigenous trees and shrubs that have been eradicated elsewhere over the past century continue to thrive within the compounds of rural churches, safeguarded by the church's values and reverence for nature (Wassie *et al.*, 2010).

The Church conserved thus forests due to Spiritual Significance the Ethiopian Orthodox faith views forests as sacred, symbolizing the Garden of Eden and divine creation (Tilahun *et al.*, 2015b). The preservation of trees around churches serves as a physical and spiritual barrier between the sacred and the profane. Church communities believe cutting trees or destroying these forests desecrates the sanctity of the church (Tura *et al.*, 2013). In addition to spiritual significance, Ethiopian Orthodox Tewahido Church way of management is important for the rest of the world by leaders and communities actively protect these forests, often through traditional norms and taboos (Wassie *et al.*, 2010). The collective responsibility ensures the forests are not encroached upon for agricultural or commercial purposes (Wassie *et al.*, 2006b). To prevent livestock grazing and agricultural encroachment, many churches have constructed stone walls around their forests (Ayalew *et al.*, 2020). The last method of the church to protect thus forests by Religious Sanctions: Violating the sanctity of these forests is discouraged through religious teachings, which often have greater influence than civil laws in these areas (Birhanu *et al.*, 2021). Even though the Ethiopian Orthodox church gives such type of services, there is no any financial support from the government or NGOs to encourage, while local communities and the church provide significant labour and moral support.

The current study highlights differences in forest management practices across various Ethiopian Orthodox church forests in distinct agroecological zones, shaped by their proximity to urban areas and local practices. Awunt Abo Monastery (Semi-Arid Zone): This monastery benefits from effective forest management due to its remote location, which shields it from community disturbances. Its wide land area and lack of burial activities contribute to its preservation. This study has similarity the study done by Dereje *et al.* (2022) carbon storage of selected church forests in northern Ethiopia: implications for climate change mitigation. Guanesa Medhanialem Church (Sub-Humid Zone): Situated near a town, this church forest faces significant disturbances from Orthodox Christian burial practices. Its limited land size exacerbates the impact of such activities. There was the same result in Dangila church forest studied by (Birhanu *et al.*, 2021). Zengebal Bedega Church (Temperate Highland Zone): Similar to Guanesa Medhanialem, this forest is near a town and also suffers degradation due to frequent burial activities. This study Urban Churches (e.g., Bahir Dar): Church forests in large cities face additional challenges, such as deforestation to accommodate infrastructure projects like community schools and commercial buildings, which are constructed to generate income for the church and support priests. These activities have led to the destruction of forested areas. The same to the above result there was results studied by (Mulat, 2013; Tilahun *et al.*, 2015b; Birhanu *et al.*, 2021; Dereje *et al.*, 2022) the recent increase in urbanization has led to significant changes in land use and land cover within cities, primarily due to deforestation and the introduction of commercial buildings. The growing population and rising demand for resources, such as forest products, have contributed to a decline in the average coverage of woody plants in churchyards. Researchers suggest that municipal authorities in urban areas, such as Bahir Dar, allocate alternative land for infrastructure projects like commercial buildings and schools. This would help preserve church forests and ensure their sustainability for religious, ecological, and community purposes. This approach underscores the importance of protecting these unique ecosystems, which serve both spiritual and ecological roles, while addressing urban development needs responsibly.

The sacred forests of the Ethiopian Orthodox Church play a major role in climate change mitigation and the conservation of native tree species (Aerts *et al.*, 2016). Studies have shown that church forests are more effective in preserving biodiversity and maintaining higher levels of biomass, carbon stocks, and tree density compared to non-church forest sites (IPCC, 2022). The current study reveals a marked and statistically significant variation in carbon stocks across the three sacred forest agroecological zones.

The aboveground biomass (AGB) results of the present study were 380.2 Mg/ha, which is higher than the values reported in previous studies. For instance,(Girma *et al.*, 2014) reported an AGB of 348.8 Mg/ha for Mount Zequalla Monastery,(Chinasho *et al.*, 2015)) reported 30.77 Mg/ha for Humbo Forest, and (Mekonnen *et al.*, 2019) found 185.71 Mg/ha for Sekele-Mariam Dry Evergreen Mountain Forest. The higher AGB observed in the current study may be attributed to differences in forest management strategies and the diameter at breast height (DBH) distribution of trees. Similarly, the belowground biomass (BGB) in this study was 95.6 Mg/ha, which also exceeds the values reported by previous studies: (Girma *et al.*, 2014) reported 47.6 Mg/ha, (Chinasho *et al.*, 2015)) reported 14.46 Mg/ha, and (Mekonnen *et al.*, 2019) reported 92.85 Mg/ha. As with the aboveground biomass, the higher BGB observed in this study could be due to effective forest management practices and structural differences in tree sizes.

Total carbon stock varied significantly across the three agroecological zones, as indicated by a one-way ANOVA ($F(3) = 354$, $p < .033$). The total carbon stock in the present study is comparable with values reported for other Ethiopian forests. For example, Sekele-Mariam Dry Evergreen Mountain Forest had a carbon stock of 127 Mg/ha (Maru *et al.*, 2023), the Gedeo community forest reported 185.71 Mg/ha (Mekonnen *et al.*, 2019), and the woodlands in the northwestern lowlands of Ethiopia had a carbon stock potential of 68.25 Mg/ha (Alemu, 2012). The current total carbon stock was 125.31 Mg/ha much greater than carbon stock potentials of woodlands, and less than the above two Sekele-Mariam Dry Evergreen Mountain Forest, Gedeo Community forest.

This study aligns closely with the mandates of both national and international organizations. At the national level, it supports the Ethiopian Environment, Forest, and Climate Change Commission (EFCCC) by providing critical insights into climate trends that can inform climate-resilient policies and sustainable resource management strategies (EFCCC, 2018). Similarly, the study aligns with the Ethiopian Ministry of Agriculture's (MoA) mission to strengthen agricultural resilience, providing practical recommendations adopting drought resistance crops and implementing enhanced irrigation systems to reduce the effect of unpredictable climate patterns on food security (MoA, 2020).

At the international level, the study aligns with the goals of the Intergovernmental Panel on Climate Change (IPCC) by contributing region-specific data to global climate models and advancing localized adaptation strategies in vulnerable regions(IPCC, 2022).

It aligns with the priorities of the Food and Agriculture Organization (FAO) by focusing on sustainable farming practices and water management systems to address the twin challenges of climate variability and food security (FAO, 2021). Through its findings and actionable recommendations, the study bridges local realities with broader institutional frameworks, highlighting its relevance to both national development agendas and global climate adaptation efforts.

7.6 Policy Implications

The results of this study demonstrate that church forests in Jabitehinan District, North West Ethiopia, possess significant potential for carbon sequestration, particularly in the semi-arid agroecological zone, which exhibited the highest total carbon stock. These findings have meaningful implications for environmental policy and land-use planning in Ethiopia and similar contexts.

Firstly, conservation strategies should prioritize the protection and restoration of church forests, especially those in semi-arid regions where their carbon storage potential is most pronounced. The high carbon stock observed in these areas highlights the value of preserving such ecosystems not only for their biodiversity and cultural significance but also for their contribution to national climate goals.

Secondly, the incorporation of church forests into land-use planning frameworks can strengthen sustainable development efforts. Integrating these forests into regional and local land-use policies can help maintain ecological balance, prevent deforestation, and enhance climate resilience. Decision-makers should consider mapping and formally recognizing these forests within spatial planning documents to ensure long-term protection.

Thirdly, the findings support the integration of church forests into climate mitigation policies. Given their measurable carbon sequestration capacity, these sacred natural sites could be included in Ethiopia's Nationally Determined Contributions (NDCs) under the Paris Agreement. Policymakers could develop incentive mechanisms, such as Payment for Ecosystem Services (PES), to support communities and religious institutions that manage and conserve these forests.

Additionally, the study underscores the importance of indigenous and faith-based conservation practices, which have preserved these forests over centuries. Recognizing and incorporating traditional ecological knowledge into formal environmental management strategies can enhance community engagement and ensure culturally appropriate interventions.

In summary, church forests are not only spiritual and cultural landmarks but also play a critical role in climate regulation and ecosystem services. Their inclusion in national conservation and climate strategies can help Ethiopia meet its environmental objectives while respecting local traditions and values.

7.7 Future Work

To build on these findings and deepen the understanding of church forests' role in climate mitigation, the following research avenues are recommended:

Future research should focus on monitoring carbon stock changes over time through longitudinal studies to assess the long-term sustainability of church forest ecosystems and understand the impacts of human activities. Additionally, analysing the carbon storage capacities of individual tree species within church forests is crucial, as it can guide species selection for restoration and afforestation programs. It is also important to examine how religious institutions, community governance structures, and local livelihoods influence forest management practices and conservation outcomes. Evaluating the role of church forests in enhancing ecosystem and community resilience to climate-related stresses, such as drought, land degradation, and biodiversity loss, will further strengthen adaptation strategies. Moreover, exploring the technical, legal, and economic feasibility of incorporating church forests into voluntary carbon markets or REDD+ programs is essential to ensure that benefits are equitably shared with local stakeholders. Finally, conducting comparative studies across different regions and countries can help generalize findings and develop a broader framework for integrating sacred natural sites into global climate mitigation policies. In conclusion, this study underscores the dual ecological and cultural value of church forests and presents them as viable nature-based solutions for climate mitigation. By bridging traditional conservation with modern scientific assessment, it opens new pathways for inclusive, community-driven environmental governance.

This study was constrained by both a limited geographical scope and a temporal limitation. It focused exclusively on church forests within the Jabitehinan District, Ethiopia which restricts the applicability of the findings to other areas that may differ in ecological conditions, cultural practices, or forest management systems. Moreover, the data were collected at a single point in time, limiting the ability to capture seasonal variations or long-term trends in carbon sequestration and forest ecosystem dynamics.

7.8 Conclusion

The average carbon stock in both aboveground and belowground components across the semi-arid, sub-humid, and temperate highland agro-ecological zones was 76.6, 12.4, and 11.2 tons/ha for aboveground biomass, and 19.2, 3.1, and 2.8 tons/ha for belowground biomass, respectively. Overall, the findings indicate that the semi-arid agro-ecological zone exhibits higher carbon stocks in woody species, which can be attributed to the presence of larger trees with greater diameters at breast height, as well as favourable environmental conditions such as increased moisture and nutrient availability.

Variations in carbon storage among the surveyed church forests in the three agro-ecological zones can be linked to several factors, including the physiognomic characteristics, species composition, and soil properties of the tree communities. In the Awuntabo Monastery, located in the semi-arid agro-ecological zone, diameter at breast height was identified as the most influential factor contributing to substantial aboveground biomass storage. The distribution of carbon stocks across different agro-ecological zones shows that aboveground biomass carbon is the highest, followed by belowground carbon.

Significant differences were observed in the aboveground and belowground carbon pools across the agro-ecological zones in this study (p-value = 0.033). Based on these findings, the present study recommends the strict protection of church forests from deforestation, encroachment, cattle interference from monasteries, and the construction of burial houses. Establishing legal frameworks and community-based conservation programs can help safeguard these forests.

This study has the potential to practical recommendations for policymakers, conservationists, and local communities.

7.9 For Policymakers

Integrate Church Forests into National Climate Policies: Recognize church forests as key components in Ethiopia's climate mitigation strategies (e.g., inclusion in Nationally Determined Contributions NDCs), Develop and fund national programs that support the conservation and sustainable management of church forests due to their carbon sequestration potential. Establish Legal Protection Frameworks: Provide legal status and protection to church forests, particularly in semi-arid regions where carbon storage is highest, and Enforce land-use regulations that prevent encroachment, illegal logging, and land conversion around these sacred sites. Promote Incentive-Based Mechanisms: Introduce Payment for Ecosystem Services (PES) or carbon credit schemes to financially reward communities and religious institutions that maintain forest cover and ecological health.

For Conservationists:

Prioritize Restoration in Degraded Church Forests: Focus reforestation and afforestation efforts in sub-humid and temperate highland zones where carbon stocks are lower but restoration potential is significant, and Use native, high-carbon-sequestering species (e.g., *Juniperus procera*) in restoration programs. Document and Integrate Indigenous Practices: Collaborate with clergy and community elders to document traditional forest management practices and integrate them into modern conservation planning, and Use participatory approaches that respect religious and cultural values. Monitor and Evaluate Carbon Stocks: Establish long-term monitoring programs using standardized protocols to track changes in carbon storage and biodiversity.

For Local Communities and Church Institutions:

Enhance Community Stewardship: Continue protecting church forests as sacred spaces, while recognizing their environmental value in climate regulation, and Encourage youth involvement and intergenerational knowledge transfer to ensure long-term commitment to conservation. Participate in Climate Education and Awareness: Engage in local climate awareness campaigns that highlight the ecological role of church forests, and Promote environmental education within religious teachings and community gatherings. Engage in Sustainable Land Use: Avoid practices like overgrazing and fuel wood collection in or near church forests, and collaborate with nearby landowners and farmers to maintain buffer zones and reduce human pressures. These recommendations aim to bridge science, policy, and community action, ensuring that the carbon sequestration potential of church forests is fully leveraged for climate mitigation and sustainable development. Contribution to Climate Change Mitigation and Future Research Directions This study makes a significant contribution to the growing body of evidence on the role of small-scale, community-managed forests in global climate change mitigation. By quantifying the carbon sequestration potential of church forests across different agroecological zones in Jabitehinan District, North West Ethiopia, the research highlights the tangible environmental value of these sacred landscapes beyond their cultural and religious importance.

The findings demonstrate that church forests, especially in semi-arid zones function as important carbon sinks, contributing to the reduction of atmospheric CO_2 levels. This reinforces the potential of integrating localized, community-based conservation efforts into national and international climate strategies, particularly in low-income and climate-vulnerable countries. The variation in carbon stocks across agroecological zones also provides critical insights for region-specific land-use planning and targeted conservation interventions. Moreover, the study affirms that indigenous knowledge systems and traditional land stewardship practices can align with contemporary environmental goals, making the case for more inclusive and culturally sensitive climate action frameworks.

Chapter Eight

Synthesis, Conclusions and Recommendations

8.1 Synthesis of the Study

The findings of this study demonstrate that climate variability, community perceptions, church forest ecology, and carbon sequestration are closely interconnected components of a single social-ecological system operating across the agroecological zones of Jabitehinan District. By integrating climatic trend analysis, community perception assessment, woody species diversity evaluation, regeneration analysis, and carbon stock estimation, the study provides a comprehensive understanding of how climate variability affects both human and ecological systems and how these interactions influence the climate mitigation potential of church forests.

The climate analysis revealed a consistent increase in temperature and a decline in seasonal and annual rainfall across the district. The observed warming trends, combined with increasing rainfall irregularity, indicate that local communities and ecosystems are experiencing substantial climatic stress. These climatic changes directly affect agricultural production, water availability, and ecosystem functioning, thereby creating conditions that shape both ecological responses and human perceptions. The findings suggest that climate variability is not merely a meteorological phenomenon but a driving force influencing socio-economic conditions and ecological processes simultaneously.

The perception study showed that farmers widely recognized declining rainfall, delayed rainfall onset, early cessation, increasing temperature, and changing planting seasons. Importantly, the perceptions reported by farmers closely corresponded with the observed meteorological trends, indicating a strong relationship between scientific climate records and local experiential knowledge. However, the level of awareness and interpretation of climate variability differed significantly among agroecological zones. Farmers in semi-arid areas reported greater awareness of climatic changes than those in sub-humid and temperate highland areas because they experience more pronounced climatic stress and greater livelihood vulnerability. This finding suggests that community perceptions are influenced by the intensity of climate impacts experienced within specific environmental contexts.

The study further revealed that climate variability influences the ecological condition of church forests through its effects on vegetation structure, species diversity, and regeneration processes. Although the three church forests collectively maintained relatively high woody species diversity, variations in diversity, regeneration status, and forest structure were observed among agroecological zones. Forests exposed to greater environmental stress exhibited weaker regeneration performance than those located in relatively favorable climatic conditions. The dominance of individuals in lower height classes and the variation in diameter class distributions among forests indicate that climatic conditions, combined with local disturbances, affect recruitment, growth, and population structure of woody species. Consequently, the long-term sustainability of biodiversity conservation in church forests is closely linked to the ability of these ecosystems to adapt to changing climatic conditions.

The regeneration findings provide an important ecological link between climate variability and future forest resilience. Regeneration is the mechanism through which forest ecosystems maintain species composition, recover from disturbance, and sustain ecosystem functions over time. The finding that three church forests exhibited good regeneration while one showed only fair regeneration suggests differences in ecological resilience among agroecological zones. Because successful regeneration depends on favorable moisture conditions, seedling establishment, and reduced environmental stress, declining rainfall and increasing temperatures may gradually reduce regenerative capacity if current climatic trends continue. This indicates that climate variability may have long-term consequences for forest sustainability even where mature forest structures currently remain intact.

The carbon stock assessment further demonstrated that differences in ecological structure and species composition translate into differences in climate mitigation potential. Church forests located in the semi-arid agroecological zone stored substantially higher amounts of carbon than those in the sub-humid and temperate highland zones. The significantly higher carbon stocks in semi-arid church forests are associated with the presence of larger mature trees and greater biomass accumulation. This finding indicates that forest structure and carbon sequestration capacity are strongly linked. It also demonstrates that church forests contribute to climate change mitigation through carbon storage, despite their relatively small size and fragmented distribution within agricultural landscapes.

Most importantly, the results reveal a functional relationship among biodiversity conservation, regeneration status, and carbon sequestration. Forests with healthier vegetation structure, larger trees, and better regeneration tend to maintain greater biomass and carbon stocks. Biodiversity supports ecosystem stability and productivity, while successful regeneration ensures the continuity of carbon storage and ecosystem services over time. Conversely, reduced regeneration resulting from climatic stress or anthropogenic disturbance may eventually lead to declines in biomass accumulation, biodiversity conservation capacity, and carbon sequestration potential. Thus, the ecological integrity of church forests directly influences their effectiveness as climate mitigation systems.

The findings also highlight the critical role of community perceptions and local institutions in sustaining these ecological functions. Church forests persist largely because local communities recognize their spiritual, cultural, and environmental importance. The observed influence of education, climate information, indigenous knowledge, extension services, and training on climate awareness suggests that informed communities are better positioned to understand climatic risks and support conservation efforts. Enhanced climate awareness may therefore strengthen community participation in forest protection, thereby contributing indirectly to biodiversity conservation, regeneration success, and carbon sequestration.

From a social-ecological systems perspective, the study demonstrates that climate variability, community perceptions, and church forest ecosystems interact through continuous feedback mechanisms. Climate variability affects livelihoods and ecosystem conditions; these changes shape community perceptions and responses; and community conservation practices influence forest biodiversity, regeneration, and carbon storage capacity. Church forests therefore function not only as ecological refugia but also as climate adaptation and mitigation assets whose sustainability depends on both ecological resilience and community stewardship.

Overall, the study provides empirical evidence that climate variability, human perceptions, biodiversity conservation, forest regeneration, and carbon sequestration are mutually reinforcing components of a single integrated system. The findings indicate that maintaining the ecological integrity of church forests enhances their climate mitigation role, while strengthening community awareness and conservation participation improves the long-term resilience of both forest ecosystems and local livelihoods. Consequently, climate adaptation and mitigation strategies in Jabitehinan District should adopt integrated approaches that simultaneously address climatic risks, community engagement, biodiversity conservation, forest regeneration, and carbon management across agroecological zones.

8.2 Conclusions

This dissertation addressed the central research problem by comprehensively examining climate variability, farmers' perceptions, forest biodiversity, and carbon stock potential in the Jabitehinan District, northwestern Ethiopia. By integrating climatic trend analysis, socio-economic perception studies, and ecological assessments of church forests, the study provided a multidimensional understanding of how climate change is manifested, perceived, and responded to within local agro-ecological contexts.

The main findings reveal a consistent decline in rainfall across all seasons alongside a significant increase in temperature over time, indicating a clear shift toward warmer and more variable climatic conditions. These changes have profound implications for rain-fed agriculture and resource management. Farmers' perceptions largely aligned with observed climatic trends, particularly regarding declining and erratic rainfall, although attribution of climate change varied, with natural, human, and religious explanations all reported. The study also demonstrated significant differences in climate perceptions across agro-ecological zones, with socio-demographic and institutional factors such as education, access to climate information, extension services, and training playing a critical role in shaping awareness. Furthermore, the ecological assessments of church forests revealed considerable variability in species diversity, structure, and regeneration across sites, while also confirming their importance as carbon sinks. Notably, the carbon stock analysis showed significant differences across agro-ecological zones, with semi-arid areas exhibiting relatively higher carbon storage potential.

Methodologically, the study's strengths lie in its mixed-methods approach and the integration of robust statistical tools, including the Mann-Kendall test, Sen's slope estimator, logistic regression, and ecological diversity indices, which enhanced the reliability and depth of the findings. The inclusion of multiple data sources meteorological records, household surveys, and field ecological measurements strengthened the validity of the conclusions. However, the study is limited by the spatial coverage of meteorological stations, potential recall bias in farmers' perception data, and the cross-sectional nature of some analyses, which may constrain the ability to capture long-term dynamics and causal relationships.

This work advances knowledge in the field by linking climate variability with both human perception and ecological response within a single, integrated framework. It moves beyond traditional climate studies by explicitly connecting biophysical changes with socio-economic and institutional factors, thereby providing a more holistic understanding of climate impacts at the local scale. The findings also contribute to the growing body of literature on the role of sacred natural sites, particularly church forests, in biodiversity conservation and climate change mitigation.

The new insights provided by this dissertation include empirical evidence on the spatial heterogeneity of climate trends within the district, the identification of key drivers influencing farmers' climate change awareness, and a detailed quantification of carbon stocks across different agro-ecological zones. Additionally, the study highlights the dual ecological and cultural significance of church forests, demonstrating their importance not only for biodiversity conservation but also for carbon sequestration and climate mitigation.

In the broader academic and practical context, this work contributes to climate change research, environmental management, and sustainable agriculture by offering evidence-based recommendations relevant to policymakers, development practitioners, and local communities. It underscores the necessity of integrating indigenous knowledge systems with scientific approaches to enhance climate resilience and supports the development of climate-smart agricultural practices tailored to local conditions.

The study suggests several areas for further investigation. Future research should consider long-term longitudinal climate data to better capture trends and variability, expand the spatial coverage of ecological assessments across more forest patches, and explore the effectiveness of specific climate adaptation strategies at the household level. Additionally, further studies could investigate the integration of indigenous knowledge with modern climate information systems, as well as the socio-ecological dynamics of church forests under increasing environmental and anthropogenic pressures.

8.3 Recommendations

1. For Policy Makers

- ❖ Recognize church forests as key ecological assets in national forest conservation and climate mitigation strategies by giving them official protective status.
- ❖ Integrate indigenous conservation practices and sacred-site protection into formal environmental and forest policy frameworks.
- ❖ Support payments for ecosystem services (PES) or carbon credit schemes that incentivize local communities and churches for maintaining forest cover and sequestering carbon.
- ❖ Develop policies that improve access to climate education, especially focusing on rural and semi-arid regions where climate impacts are more severe.
- ❖ Strengthen research and data-sharing networks between national meteorological services, universities, and local administrations to enhance evidence-based planning.
- ❖ Encourage collaborative governance models, where religious institutions, community groups, and government agencies jointly manage natural resources.

2. For Universities

- ❖ Practical training, field demonstrations, and community-based learning approaches should be emphasized to bridge the gap between theory and practice. Special attention should be given to improving farmers' access to climate information services, as the study shows that education and extension support significantly influence perception and adaptive capacity.
- ❖ Actively engage in documenting, conserving, and promoting indigenous knowledge systems alongside scientific knowledge. Establishing community-based research centers or living

laboratories in rural areas can further strengthen knowledge exchange and sustainable resource management.

3. For NGOs

- ❖ Prioritize awareness creation and capacity-building initiatives aimed at improving farmers' understanding of climate variability and adaptation strategies. Since perception is strongly influenced by access to information and extension services, NGOs can play a critical role in strengthening local communication systems, including farmer training, workshops, and the dissemination of timely climate information.
- ❖ Support the conservation and sustainable management of church forests and other natural ecosystems. These forests not only preserve biodiversity but also serve as significant carbon sinks, particularly in semi-arid areas. Community-based forest management programs, combined with incentives for conservation (such as carbon financing or payment for ecosystem services), can enhance both environmental and livelihood outcomes.
- ❖ Foster multi-stakeholder partnerships involving local communities, government agencies, and academic institutions. Such collaborations are essential for scaling up successful adaptation strategies, ensuring policy alignment, and promoting sustainable development in the face of ongoing climate change.

4. For Church Administrators

- ❖ Strengthen the existing traditional protection of church forests by establishing community-based forest monitoring groups to prevent illegal logging, encroachment, and grazing.
- ❖ Promote replanting and assisted natural regeneration of indigenous tree species, especially in areas where regeneration rates are slow or where mature trees dominate.
- ❖ Facilitate environmental education within the church community by integrating teachings on environmental stewardship, biodiversity conservation, and climate responsibility into religious programs.
- ❖ Collaborate with agricultural offices and environmental agencies to obtain seedlings, training, and technical support for forest management and conservation.
- ❖ Develop church forest boundary demarcation and documentation to prevent land-use dispute and ensure long-term forest protection.

- ❖ Encourage the use of church forests as demonstration sites for climate change awareness, carbon sequestration education, and ecological restoration.

5. For Farmers

- ❖ Adopt climate-smart agricultural practices, including drought-tolerant crop varieties, crop rotation, intercropping, mulching, and water harvesting techniques to cope with decreasing rainfall and rising temperatures.
- ❖ Shift planting and harvesting schedules based on seasonal climate forecasts and local indigenous early warning signals to reduce crop failure caused by unpredictable rainfall onset and cessation.
- ❖ Participate in training provided by agricultural extension workers to improve understanding of climate variability and its implications for farming decisions.
- ❖ Engage in soil and water conservation activities, such as terracing, contour ploughing, and agroforestry, to enhance soil fertility and moisture retention.
- ❖ Cooperate with church conservation activities by reducing pressure on church forests, including avoiding livestock grazing inside forest boundaries and refraining from unauthorized tree cutting.

6. For Government Administrators

- ❖ Strengthen extension service coverage with regular training programs designed to build farmers' climate change awareness and adaptation skills.
- ❖ Expand irrigation infrastructure and water harvesting systems to reduce dependence on erratic rainfall patterns and ensure year-round agricultural production.
- ❖ Support the establishment of community-managed nurseries producing indigenous tree species for both farmland agroforestry and church forest enrichment.
- ❖ Facilitate land-use planning that prioritizes the conservation of remaining natural vegetation and recognizes church forests as protected ecological zones.
- ❖ Provide technical and financial support for biodiversity monitoring, carbon stock assessment, and forest restoration initiatives.
- ❖ Promote climate information dissemination through radio programs, local meetings, and mobile platforms to improve local decision-making.

The combined findings of the four studies show that climate change is affecting rainfall patterns, temperature trends, agricultural livelihoods, and ecosystem stability in Jabitehinan District. Farmers' level of awareness and adaptive capacity is closely linked to education, information access, and institutional support. Meanwhile, church forests serve as vital ecological refuges, preserving biodiversity and storing significant amounts of carbon. Effective responses require integrated efforts that unite local knowledge, religious stewardship, scientific guidance, and policy support.

8.4 Future Studies

This study demonstrated that climate variability in the Jabitehinan district is already evident through fluctuations in rainfall and rising temperatures, yet further research is needed to deepen the understanding of its long-term implications. Future studies should employ high-resolution climate models and downscaled projections to assess how rainfall and temperature trends may evolve under different climate change scenarios. Such work would provide more accurate forecasts for agricultural planning, water resource management, and disaster preparedness, ensuring that local adaptation strategies are evidence-based and forward-looking.

Building on the insights into farmers' perceptions, future research should explore how adaptive behaviours evolve when communities are provided with improved climate information and institutional support. Longitudinal studies could track how access to irrigation, extension services, and indigenous early warning systems influence shifts in perceptions and adaptation practices over time. Furthermore, integrating cultural and religious perspectives into climate communication strategies deserves more attention, as this may enhance acceptance and effectiveness of climate awareness campaigns in rural communities.

The analysis of church forests highlighted their ecological and climate mitigation significance, but additional studies should focus on the long-term monitoring of species composition, regeneration dynamics, and carbon sequestration potential. Advanced techniques such as remote sensing, GIS-based forest mapping, and drone-based biomass estimation could provide more precise assessments of forest health and carbon stock changes. Research should also investigate the socio-economic trade-offs between conservation and local resource use, offering evidence for designing sustainable community-based forest management systems.

Reference

Abebaw, Sintayehu Eshetu (2025). A global review of the impacts of climate change and variability on agricultural productivity and farmers' adaptation strategies. *13*(5), e70260.

Abeje, Abiyot, & Alemayehu, Melkamu (2019). Impacts of climate change on crop production and its adaptation and mitigation strategies in Ethiopia. *4*(2), 23-35.

Abtew, Wossenu, Melesse, Assefa M, & Dessalegne, Tibebe (2009). Spatial, inter and intra-annual variability of the Upper Blue Nile Basin rainfall. *23*(21), 3075-3082.

Ademe, Dereje, Zaitchik, Benjamin F, Tesfaye, Kindie, Simane, Belay, Alemayehu, Getachew, & Adgo, Enyew (2020). Climate trends and variability at adaptation scale: Patterns and perceptions in an agricultural region of the Ethiopian Highlands. *29*, 100263.

Adeoti, Ai, Coster, As, & Akanni. (2016). Analysis of farmers' vulnerability, perception and adaptation to climate change in Kwara State, Nigeria. *1*(1), 1-16.

Aerts, Raf, Van Overtveld, Koen, November, Eva, Wassie, Alemayehu, Abiyu, Abrham, Demissew, Sebsebe, Daye, Desalegn D, Giday, Kidane, Haile, Mitiku, & Tewoldeberhan, Sarah (2016). Conservation of the Ethiopian church forests: threats, opportunities and implications for their management. *551*, 404-414.

Africandevelopmentbank. (2024). State of climate in Africa 2023 report insights *1*(1), 1-17.

Ahammad, Ronju, Stacey, Natasha, Eddy, Ian Ms, Tomscha, Stephanie A, & Sunderland, Terry Ch (2019). Recent trends of forest cover change and ecosystem services in eastern upland region of Bangladesh. *647*, 379-389.

Ahmed, Syed Imran, Rudra, Ramesh, Dickinson, Trevor, & Ahmed, Motahir. (2014a). Trend and periodicity of temperature time series in Ontario. *American Journal of Climate Change*, *3*(03), 272.

Ahmed, Syed Imran, Rudra, Ramesh, Dickinson, Trevor, & Ahmed, Motahir (2014b). Trend and periodicity of temperature time series in Ontario. *3*(03), 272.

Ahrens, Bodo. (2006). Distance in spatial interpolation of daily rain gauge data. *Hydrology and Earth System Sciences, 10*(2), 197-208.

Ahrens, Bodo J Hydrology, & Sciences, Earth System. (2006). Distance in spatial interpolation of daily rain gauge data. *10*(2), 197-208.

Aidoo, Danley Colecraft, Boateng, Seth Dankyi, Freeman, Comfort Kudadjie, & Anaglo, Jonathan Nicholas (2021). The effect of smallholder maize farmers' perceptions of climate change on their adaptation strategies: the case of two agro-ecological zones in Ghana. *7*(11).

Akanbi, Remilekun T, Davis, Nerhene, & Ndarana, Thando (2021). Climate change and maize production in the Vaal catchment of South Africa: assessment of farmers' awareness, perceptions and adaptation strategies. *82*, 191-209.

Akano, Oreoluwa, Modirwa, Sinah, Oluwasemire, Kolapo, & Oladele, Oladimeji (2023). Awareness and perception of climate change by smallholder farmers in two agroecological zones of Oyo state Southwest Nigeria. *88*(1), 39-68.

Alam, Gm Monirul, Alam, Khorshed, & Mushtaq, Shahbaz (2017). Climate change perceptions and local adaptation strategies of hazard-prone rural households in Bangladesh. *17*, 52-63.

Alba, Pedro, Bliss-Guest, Patricia, & Tuck, Laura (2023). Reforming the World Bank to play a critical role in addressing climate change.

Alemayehu. (2022). Spatiotemporal rainfall and temperature variability in Suha watershed, Upper Blue Nile Basin, Northwest Ethiopia. *194*(8), 538.

Alemayehu, Arragaw, Maru, Molla, Bewket, Woldeamlak, & Assen, Mohammed (2020a). Spatiotemporal variability and trends in rainfall and temperature in Alwero watershed, western Ethiopia. *9*(1), 1-15.

Alemayehu, Arragaw, Maru, Molla, Bewket, Woldeamlak, & Assen, Mohammed (2020b). Spatiotemporal variability and trends in rainfall and temperature in Alwero watershed, western Ethiopia. *9*, 1-15.

Alemayehu, Arragaw, Minale, Amare Sewnet, & Legesse, Solomon Addisu (2022). Spatiotemporal rainfall and temperature variability in Suha watershed, Upper Blue Nile Basin, Northwest Ethiopia. *194*(8), 538.

Alemneh, Derebe (2021). Ethnobotanical survey of medicinal plants in Yilmana Densa and Quarit districts, west Gojjam, Western Ethiopia. *2021*.

Alemu. (2019). Watershed-Based Rainfall variability and trends of extreme rainfall events in South East Awash Basin, Ethiopia. *6*, 5524-5530.

Aniye, Henok W/Yohannes, Bekele, Tsegaye, & Worku, Walelign (2025). Trends of climate variability and its association with farmers' perceptions of climate change in Gassera district, southeastern Ethiopia. *15*(1), 4399.

Aregie, Asersie, & Tolera, Motuma. (2019). Asersie Mekonnen, Motuma Tolera. Carbon Stock Estimation Along Altitudinal Gradient in Sekele-Mariam Dry Evergreen Montane Forest. *Agriculture, Forestry and Fisheries, 8*, 48-53. doi:10.11648/j.aff.20190802.14

Arıkan, Gizem, & Günay, Defne (2021). Public attitudes towards climate change: A cross-country analysis. *23*(1), 158-174.

Asekun-Olarinmoye, Esther O, Bamidele, James O, Odu, Olusola O, Olugbenga-Bello, Adenike I, Abodurin, Olugbenga L, Adebimpe, Wasiu O, Oladele, Edward A, Adeomi, Adeleye A, Adeoye, Oluwatosin A, & Ojofeitimi, Ebenezer (2014). Public perception of climate change and its impact on health and environment in rural southwestern Nigeria. 1-10.

Asfaw, Amogne, Simane, Belay, Hassen, Ali, & Bantider, Amare (2018). Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin. *19*, 29-41.

Asner, Gregory P, Mascaro, Joseph, Muller-Landau, Helene C, Vieilledent, Ghislain, Vaudry, Romuald, Rasamoelina, Maminiaina, Hall, Jefferson S, & Van Breugel, Michiel. (2012). A universal airborne LiDAR approach for tropical forest carbon mapping. *Oecologia, 168*(4), 1147-1160.

Asrat, Paulos, & Simane, Belay. (2018). Farmers' perception of climate change and adaptation strategies in the Dabus watershed, North-West Ethiopia. *Ecological processes, 7*(1), 1-13.

Assefa, Genene, Mengistu, Tefera, Getu, Zerihun, & Zewdie, Solomon. (2013). Training manual on: Forest carbon pools and carbon stock assessment in the context of SFM and REDD+. *Hawassa University Wondo Genet College of Forestry and Natural Resources, Wondo Genet*.

Ayalew, Dereje, Tesfaye, Kindie, Mamo, Girma, Yitaferu, Birru, & Bayu, Wondimu (2012). Variability of rainfall and its current trend in Amhara region, Ethiopia. *7*(10), 1475-1486.

Ayalew, T, Merawi, E, & Alemu. (2020). Woody plant species diversity of Shello Giorgis dry Afromontane forest, Farita district, west Amhara, Ethiopia. *4*(1), 59-65.

Abramoff, Rose Z. (2015). *Phenology and allocation of belowground plant carbon at local to global scales.* Boston University,

Agrawal, Arun, & Agrawal, Arun. (2008). *The role of local institutions in adaptation to climate change* (Vol. 17): World Bank Washington, DC.

Aklilu, A, & Alebachew, A. (2009). *Assessment of climate change-induced hazards, impacts and responses in the southern lowlands of Ethiopia. Forum for Social Studies*. Retrieved from

Alem, Shiferaw, Hassen, Nesru, Teshome, Mindaye, Sisay, Kibruyesfa, Teshager, Zelalem, Yahya, Nesibu, & Eshete, Abeje. (2022). Floristic composition, diversity, population structure and regeneration status of woody species in four church forests in Ethiopia. In *State of the Art in Ethiopian Church Forests and Restoration Options* (pp. 127-149): Springer.

Alemu, By. (2012). *Carbon stock potentials of woodlands and land use and land cover changes in north western lowlands of Ethiopia.* Hawassa University,

Anrspc. (2017). *Water Resources and Environmental Profile of the Amhara Region. Bahir Dar, Ethiopia.* Retrieved from

Bahiru, W, Wende, E, Mohammed, L, Mohammed, Y, Adem, H, & Demmisie. (2020). Assessing the impact of rainfall variability on teff production and farmers perception at Gubalafto district, North Eastern, Ethiopia. *6*, 042.

Bazezew, Muluken Nega, Soromessa, Teshome, & Bayable, Eyale (2015). Carbon stock in Adaba-Dodola community forest of Danaba District, West-Arsi zone of Oromia Region, Ethiopia: An implication for climate change mitigation. *7*(1), 14-22.

Beekle. (2007). Useful trees of Ethiopia: Identification, propagation and management in 17 agroecological zones. World Agroforestry Centre.

Belay, Abrham, Recha, John W, Woldeamanuel, Teshale, & Morton, John F. (2017a). Smallholder farmers’ adaptation to climate change and determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. *Agriculture & Food Security, 6*(1), 1-13.

Belay, Abrham, Recha, John W, Woldeamanuel, Teshale, & Morton, John F (2017b). Smallholder farmers’ adaptation to climate change and determinants of their adaptation decisions in the Central Rift Valley of Ethiopia. *6*(1), 24.

Bhattacharjee, Jyoti, & Roy, Subhasis (2024). Understanding Global Climatic Shifts-A Comprehensive Review. *133*, 2-11.

Birhanie Addisu Bitew, & Ayalew, Mengistu Daniel. (2025). Spatio-temporal variability of Temperature and rainfall in the Jabitehinan District in North West Ethiopia. *57*(2).

Birhanu, Tayachew, Mohammed, Ali Seid, & Mekonnen, Amare Bitew. (2021). Floristic composition, structure and regeneration status of woody plants in church forests of Dangila, Northwestern Ethiopia. *7*(1), 1911438.

Biswas, Bikram, Roy, Sajib Kumar, Ullah, Mohammad Nur, & Mukharjee, Shanjay Kumar (2021). Public perceptions about the impact of climate change on human health: a study of Bangladesh. *5*(2), ep21012.

Blein, Roger, Bwalya, Martin, Chimatiro, Sloans, Faivre-Dupaigre, Benoît, Kisira, Simon, Leturque, Henri, & Wambo-Yamdjeu, Augustin. (2017). Agriculture in Africa: transformation and outlook.

Bongers, Fjjm, Wassie, Alemayehu, Sterck, Frank J, Bekele, Tesfaye, & Teketay, Demel (2006). Ecological restoration and church forests in northern Ethiopia. *1*(1), 35-44.

Bonorino, Gustavo, Osterkamp, Wr, & Colombo, F. (2002). An averaging procedure for applying the Revised Universal Soil Loss Equation (RUSLE) to disturbed mountain watersheds.

Bora, Nepolion, Nath, Arun Jyoti, & Das, Ashesh Kumar (2013). Aboveground biomass and carbon stocks of tree species in tropical forests of Cachar District, Assam, Northeast India. *39*(2), 97-106.

Brown, Sandra. (2002). Measuring carbon in forests: current status and future challenges. *Environmental pollution, 116*(3), 363-372.

Balogh, Werner, & Kurino, Toshiyuki. (2020). The world meteorological organization and space-based observations for weather, climate, water and related environmental services. In *Space capacity building in the XXI century* (pp. 223-232): Springer.

Bewket, Woldeamlak. (2009). *Rainfall variability and crop production in Ethiopia: Case study in the Amhara region.* Paper presented at the Proceedings of the 16th international conference of Ethiopian studies.

Bourekba, Moussa. (2021). Climate change and violent extremism in north Africa. In: CASCADES Research Paper. Barcelona: Barcelona Centre for International Affairs.

Brown. (1997). *Estimating biomass and biomass change of tropical forests: a primer (Vol. 134). Food & Agriculture Org.* (1354-1013). Retrieved from

Canadell, J, Jackson, Rb, Ehleringer, Jr, Mooney, Ha, Sala, Oe, & Schulze. (2021). Maximum Rooting Depth of Vegetation Types at the Global Scale. Oecologia [en línea], vol. 108, no. 4. *3*, 583-595.

Canadell, Josep G, & Raupach, Michael R. (2008). Managing forests for climate change mitigation. *Science, 320*(5882), 1456-1457.

Capstick, Stuart, Whitmarsh, Lorraine, Poortinga, Wouter, Pidgeon, Nick, & Upham, Paul (2015). International trends in public perceptions of climate change over the past quarter century. *6*(1), 35-61.

Cardelús, Catherine L, Lowman, Margaret D, & Eshete, Alemaheyu Wassie (2012). Uniting church and science for conservation. *335*(6071), 915-917.

Cardelús, Catherine L, Scull, Peter, Hair, Joshua, Baimas-George, Maria, Lowman, Margaret D, & Wassie Eshete, Alemaheyu (2013). A preliminary assessment of Ethiopian sacred grove status at the landscape and ecosystem scales. *5*(2), 320-334.

Cardelús, Catherine L, Woods, Carrie L, Bitew Mekonnen, Amare, Dexter, Sonya, Scull, Peter, & Tsegay, Berhanu Abraha (2019). Human disturbance impacts the integrity of sacred church forests, Ethiopia. *14*(3), e0212430.

Chakraborty, Shiulee, Pandey, Rp, Chaube, Uc, & Mishra, Sk (2013). Trend and variability analysis of rainfall series at Seonath River Basin, Chhattisgarh (India). *2*(4), 425-434.

Chala, Dechassa, Belay, Simane, & Bamlaku, Alamerew (2020). Analysis of farmers perceived and observed climate variability and change in Didessa sub-basin, Blue Nile River, Ethiopia. *15*(2), 149-164.

Chao, Anne, Chiu, Chun-Huo, & Jost, Lou (2014). Unifying species diversity, phylogenetic diversity, functional diversity, and related similarity and differentiation measures through Hill numbers. *45*(1), 297-324.

Chattopadhyay, Somsubhra, & Edwards, Dwayne (2016). Long-term trend analysis of precipitation and air temperature for Kentucky, United States. *4*(1), 10.

Chave, Jérôme, Andalo, Christophe, Brown, Sandra, Cairns, Michael A, Chambers, Jeffrey Q, Eamus, Derek, Fölster, Horst, Fromard, François, Higuchi, Niro, & Kira, Tatuo. (2005a). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, *145*(1), 87-99.

Chave, Jérôme, Andalo, Christophe, Brown, Sandra, Cairns, Michael A, Chambers, Jeffrey Q, Eamus, Derek, Fölster, Horst, Fromard, François, Higuchi, Niro, & Kira, Tatuo. (2005b). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *145*, 87-99.

Cheval, Sorin, Bulai, Ana, Croitoru, Adina-Eliza, Dorondel, Ștefan, Micu, Dana, Mihăilă, Dumitru, Sfîcă, Lucian, & Tișcovschi, Adrian (2022). Climate change perception in Romania. *149*(1), 253-272.

Chinasho, Alefu, Soromessa, Teshome, & Bayable, Eyale (2015). Carbon stock in woody plants of Humbo forest and its variation along altitudinal gradients: the case of Humbo district, Wolaita zone, southern Ethiopia. *3*(4), 97-103.

Christensen, Jens Hesselbjerg, & Christensen, Ole Bøssing. (2007). A summary of the PRUDENCE model projections of changes in European climate by the end of this century. *Climatic Change, 81*(1), 7-30.

Collier, Paul, Conway, Gordon, & Venables, Tony (2008). Climate change and Africa. *24*(2), 337-353.

Comas, Louise, Becker, Steven, Cruz, Von Mark V., Byrne, Patrick F., & Dierig, David A. (2013). Root traits contributing to plant productivity under drought. *4*. doi:10.3389/fpls.2013.00442

Conway, Declan, & Schipper, E Lisa F (2011). Adaptation to climate change in Africa: Challenges and opportunities identified from Ethiopia. *21*(1), 227-237.

Costanza, Robert, D'arge, Ralph, De Groot, Rudolf, Farber, Stephen, Grasso, Monica, Hannon, Bruce, Limburg, Karin, Naeem, Shahid, O'neill, Robert V, & Paruelo, Jose (1997). The value of the world's ecosystem services and natural capital. *387*(6630), 253-260.

Coyle, Caitlin E, Schulman-Green, Dena, Feder, Shelli, Toraman, Sinem, Prust, Margaret L, Plano Clark, Vicki L, & Curry, Leslie (2018). Federal funding for mixed methods research in the health sciences in the United States: Recent trends. *12*(3), 305-324.

Creswell, John W, & Clark, Plano. (2023). Revisiting mixed methods research designs twenty years later. *1*(1), 21-36.

Creswell, John W, & Clark, Vickil Plano (2007). Mixed methods research.

Care International Poverty, Environment, & Network, Climate Change. (2011). Understanding Vulnerability to Climate Change: insights from Application of CARE's Climate

Vulnerability and Capacity Analysis (CVCA) Methodology. In: CARE International Poverty, Environment and Climate Change Network Bangkok ….

Chih-Pei, Hu, & Chang, Yan-Yi. (2017). John W. Creswell, research design: Qualitative, quantitative, and mixed methods approaches. In.

Creswell, John W. (1999). Mixed-method research: Introduction and application. In *Handbook of educational policy* (pp. 455-472): Elsevier.

Creswell, John W, & Clark, Vicki L Plano. (2017). *Designing and conducting mixed methods research*: Sage publications.

Daninga, Phillip Daniel, Mlowosa, Tiberius, & Zhao, Sijian (2015). FARMERS'PERCEPTION AND ADAPTATION STRATEGIES TO CLIMATE CHANGE INDICATORS IN MOROGORO. *3*(1), 1-13.

Dar, Javid Ahmad, Subashree, Kothandaraman, Raha, Debojyoti, Kumar, Ashwani, Khare, Pramod Kumar, & Khan, Mohammed Latif (2019). Tree diversity, biomass and carbon storage in sacred groves of Central India. *26*, 37212-37227.

Daye, Desalegn Desissa, & Healey, John (2015). Impacts of land-use change on sacred forests at the landscape scale. *3*, 349-358.

Debebe, Belete, Senbeta, Feyera, Teferi, Ermias, Diriba, Dawit, & Teketay, Demel (2023). Analysis of forest cover change and its drivers in biodiversity hotspot areas of the semien mountains national Park, northwest Ethiopia. *15*(4), 3001.

Degefu, Mekonnen Adnew, & Bewket, Woldeamlak (2014). Variability and trends in rainfall amount and extreme event indices in the Omo-Ghibe River Basin, Ethiopia. *14*, 799-810.

Delaney, Matt, Brown, Sandra, Lugo, Ariel E, Torres-Lezama, Armando, & Quintero, Narsizo Bello. (1998). The quantity and turnover of dead wood in permanent forest plots in six life zones of Venezuela 1. *Biotropica*, *30*(1), 2-11.

Dereje, Kehali, Soromessa, Teshome, & Eshete, Abeje (2022). Carbon storage of selected church forests in northern Ethiopia: implications for climate change mitigation. *10*(1), 25-48.

Deressa, Temesgen Tadesse, Hassan, Rashid M, & Ringler, Claudia. (2011a). Perception of and adaptation to climate change by farmers in the Nile basin of Ethiopia. *The Journal of Agricultural Science*, *149*(1), 23-31.

Deressa, Temesgen Tadesse, Hassan, Rashid M, & Ringler, Claudia (2011b). Perception of and adaptation to climate change by farmers in the Nile basin of Ethiopia. *149*(1), 23-31.

Dhaulkhandi, Manoj, Dobhal, Asha, Bhatt, Sunil, & Kumar, Munesh (2008). Community structure and regeneration potential of natural forest site in Gangotri, India. *4*(1), 49-52.

Dhyani, Shalini, Sivadas, Deepu, Basu, Oindrila, & Karki, Madhav (2022). Ecosystem health and risk assessments for high conservation value mountain ecosystems of South Asia: A necessity to guide conservation policies. *1*(1), 211-225.

Dias, Nunes And. (2022). Perception of climate change effects over time and the contribution of different areas of knowledge to its understanding and mitigation. *10*(1), 7.

Díaz, Sandra Myrna, Settele, Josef, Brondízio, Eduardo, Ngo, Hien, Guèze, Maximilien, Agard, John, Arneth, Almut, Balvanera, Patricia, Brauman, Kate, & Butchart, Stuart. (2019). The global assessment report on biodiversity and ecosystem services: Summary for policy makers.

Dingamo, T, Takele, S, Woldu, Z, & Demissew. (2021). Vegetation structure and regeneration status of the western escarpment of the rift valley of the Gamo zone, southern Ethiopia. *11*(10), 13-23.

Dioha, Emmanuel C, Chung, Eun-Sung, Song, Jae Yeol, & Ayugi, Brian Odhiambo (2026). Future projections of aridity change across Africa's climatic regions. 108916.

Denison, Ian, & Wauchope, Samantha. (2024). United Nations Educational, Scientific and Cultural Organization (UNESCO). In *Encyclopedia of Quality of Life and Well-Being Research* (pp. 7361-7366): Springer.

Dinku, T. (2010). *Climate risk management and data needs for agriculture in Ethiopia.* Paper presented at the Strengthening capacity for climate change adaptation in the agriculture sector in Ethiopia; Proceedings from National Workshop held in Nazreth, Ethiopia.

Distictagricultureoffice. (2020). *Annual report for the district agricultural producttion and other sector implementation* (0378-1127). Retrieved from

Easterling, William E, Aggarwal, Pramod K, Batima, Punsalmaa, Brander, Keith M, Erda, Lin, Howden, S Mark, Kirilenko, Andrei, Morton, John, Soussana, Jean-François, & Schmidhuber, Josef (2007). Food, fibre and forest products. *2007*, 273-313.

Ebrahim, Ahmed Aliy, Miheretu, Birhan Asmame, & Alemayehu, Arragaw. (2022). Vulnerability of smallholder farmers to climate variability and change across different agro-ecological Zones in Oromo Nationality Administration (ONA), North east Ethiopia. *17*(6), e0268094.

Elum, Zelda A, Modise, David M, & Marr, Ana (2017). Farmer's perception of climate change and responsive strategies in three selected provinces of South Africa. *16*, 246-257.

Endalew, Birara, Wondimagegnhu, Beneberu Assefa, & Tassie, Kassahun (2020). Willingness to pay for church forest conservation: A case study in northwestern Ethiopia. *66*(3), 105.

Enyew, Fekadie Bazie, & Wassie, Simachew Bantigegn (2024). Rainfall trends and spatiotemporal patterns of meteorological drought in Menna watershed, northwestern Ethiopia. *10*(6).

Esayas, Befikadu, Simane, Belay, Teferi, Ermias, Ongoma, Victor, & Tefera, Nigussie (2019). Climate variability and farmers' perception in Southern Ethiopia. *2019*(1), 7341465.

Etikan, Ilker, Musa, Sulaiman Abubakar, & Alkassim, Rukayya Sunusi (2016). Comparison of convenience sampling and purposive sampling. *5*(1), 1-4.

Efccc. (2018). *Ethiopia's forest reference level submission to the UNFCCC. Ministry of Environment, Forest and Climate Change.* Retrieved from

Eshete, Alemayehu Wassie. (2007). *Ethiopian church forests: opportunities and challenges for restoration*: Wageningen University and Research.

FAO. (2012). Harmonized World Soil Database (HWSD). *244*, 108258.

FAO. (2015). The Global Forest Resources Assessment Desk reference; FRA Country Reports; Food and Agriculture Organization of the United Nations Rome, Italy., *22*, 159-177.

FAO. (2005). *Global Forest Resource Assessment. FAO Forestry Paper 147. Food and Agriculture Organization of the United Nations, Rome, Italy*. (0521804957). Retrieved from

FAO. (2018). *Climate-smart agriculture sourcebook. Food and Agriculture Organization.* (Vol. 90): [Wiley, British Ecological Society].

FAO. (2020). *Global Forest Resources Assessment (Ethiopia data). Food and Agriculture Organization of the United Nations.* Retrieved from

FAO. (2021). *The state of food and agriculture 2021: Making agrifood systems more resilient to shocks and stresses.* (2580-2844). Retrieved from

Fearnside, Philip M. (1999). Forests and global warming mitigation in Brazil: opportunities in the Brazilian forest sector for responses to global warming under the "clean development mechanism". *Biomass and Bioenergy*, *16*(3), 171-189.

Feke, Belay Ejigu, Terefe, Tadesse, Ture, Kassahun, & Hunde, Debela (2021). Spatiotemporal variability and time series trends of rainfall over northwestern parts of Ethiopia: the case of Horro Guduru Wollega Zone. *193*(6), 367.

Ferede, Tadele, Ayenew, Ashenafi Belayneh, Hanjra, Munir A, & Hanjra, M. (2013). Agroecology matters: Impacts of climate change on agriculture and its implications for food security in Ethiopia. *Global food security: Emerging issues and economic implications*, 71-112.

Feyissa, Adugna, Soromessa, Teshome, & Argaw, Mekuria (2013). Forest carbon stocks and variations along altitudinal gradients in Egdu Forest: Implications of managing forests for climate change mitigation. *2*(4), 40-46.

Forster, Piers M, Smith, Chris, Walsh, Tristram, Lamb, William F, Lamboll, Robin, Cassou, Christophe, Hauser, Mathias, Hausfather, Zeke, Lee, June-Yi, & Palmer, Matthew (2025). Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence. *2025*, 1-72.

Fosu-Mensah, Benedicta Y, Vlek, Paul Lg, & Maccarthy, Dilys Sefakor. (2012a). Farmers' perception and adaptation to climate change: a case study of Sekyedumase district in Ghana. *Environment, development and sustainability, 14*(4), 495-505.

Fosu-Mensah, Benedicta Y, Vlek, Paul Lg, & Maccarthy, Dilys Sefakor (2012b). Farmers' perception and adaptation to climate change: a case study of Sekyedumase district in Ghana. *14*, 495-505.

Franklin, Jerry F, Shugart, Herman H, & Harmon, Mark E. (1987). Tree death as an ecological process. *BioScience, 37*(8), 550-556.

Friedlingstein, Pierre, O'sullivan, Michael, Jones, Matthew W, Andrew, Robbie M, Gregor, Luke, Hauck, Judith, Le Quéré, Corinne, Luijkx, Ingrid T, Olsen, Are, & Peters, Glen (2022). Global carbon budget 2022. *14*(11), 4811-4900.

Gadédjisso-Tossou, Agossou (2015). Understanding farmers' perceptions of and adaptations to climate change and variability: The case of the Maritime, Plateau and Savannah Regions of Togo. *6*(12), 1441.

Gatti, Luciana V, Basso, Luana S, Miller, John B, Gloor, Manuel, Gatti Domingues, Lucas, Cassol, Henrique Lg, Tejada, Graciela, Aragão, Luiz Eoc, Nobre, Carlos, & Peters, Wouter (2021). Amazonia as a carbon source linked to deforestation and climate change. *595*(7867), 388-393.

Gautam, Ritesh, Hsu, Nc, Lau, K-M, Tsay, S-C, & Kafatos, Menas (2009). Enhanced pre-monsoon warming over the Himalayan-Gangetic region from 1979 to 2007. *36*(7).

Gebeyehu, Getaneh, Soromessa, Teshome, Bekele, Tesfaye, & Teketay, Demel (2019). Carbon stocks and factors affecting their storage in dry Afromontane forests of Awi Zone, northwestern Ethiopia. *43*(1), 1-18.

Gebreegziabher, Zenebe, Mekonnen, Alemu, Bekele, Rahel Deribe, Zewdie, Samuel Abera, & Kassahun, Meseret Molla (2020). Crop-Livestock inter-linkages and climate change implications for Ethiopia's agriculture: a Ricardian approach. 615-640.

Gebrehiwot, Tagel, & Van Der Veen, Anne (2021). Farmers' drought experience, risk perceptions, and behavioural intentions for adaptation: Evidence from Ethiopia. *13*(6), 493-502.

Gebrehiwot, Tagel, Van Der Veen, Anne, & Maathuis, Ben (2011). Spatial and temporal assessment of drought in the Northern highlands of Ethiopia. *13*(3), 309-321.

Gebresellase, Selamawit Haftu, Wu, Zhiyong, Muhammad, Wada Idris, & Haile, Gebremedhin Gebremeskel (2025). Projected impacts of climate and land use changes on streamflow extremes in the upper awash Basin, Ethiopia. 100806.

Getachew, Abate, Teshome, Asaminew, & Demissie, Teferi Dejene. (2023). Assessment of 'Kiremt'2023 Climate and Climate Outlook of the Upcoming 'Bega'2023/24.

Getachew, Tesfaye, Belew, Derbew, & Tulu, Solomon. (2012). Combined Effect of Plant Spacing and Time of Earthing up on Tuber Quality Parameters of Potato(Solanum tuberosum L.) at Degem District, North Showa Zone of Oromia Regional State. *Asian journal of crop science, 5*(1), 24-32.

Getaneh, Habtam, & Seid, Ali (2015). Floristic composition, structure and regeneration status of Achera natural forest in Chilga district, northwest Ethiopia. *14*(2), 217-231.

Girma, Abel, Soromessa, Teshome, & Bekele, Tesfaye (2014). Forest carbon stocks in woody plants of Mount Zequalla Monastery and it's variation along altitudinal gradient: implication of managing forests for climate change mitigation. *3*(2), 132-140.

Girona, Miguel Montoro, Aakala, Tuomas, Aquilué, Núria, Bélisle, Annie-Claude, Chaste, Emeline, Danneyrolles, Victor, Díaz-Yáñez, Olalla, D'orangeville, Loïc, Grosbois, Guillaume, & Hester, Alison. (2023). Challenges for the sustainable management of the boreal forest under climate change. In *Boreal Forests in the face of climate change: sustainable management* (pp. 773-837): Springer.

Gissila, T, Black, E, Grimes, Dif, & Slingo. (2004). Seasonal forecasting of the Ethiopian summer rains. *24*(11), 1345-1358.

Gobena, Abate. (2018). Importance of teaching and practices of Ethiopian Orthodox Tewahedo Church in forest biodiversity conservation.

Gujube, Alefu. (2015). Carbon Stock in Woody Plants of Humbo Forest and its Variation along Altitudinal Gradients: The Case of Humbo District, Wolaita Zone, Southern Ethiopia. *International Journal of Environmental Protection and Policy, 3*, 97. doi:10.11648/j.ijepp.20150304.13

Hare, William (2003). Assessment of knowledge on impacts of climate change–contribution. *100*(6), 25-35.

Hairiah, Kurniatun, Sitompul, Sm, Van Noordwijk, Meine, & Palm, Cheryl. (2001). *Methods for sampling carbon stocks above and below ground*: ICRAF Bogor, Indonesia.

Harmon, Mark E, & Sexton, Jay. (1996). Guidelines for measurements of woody detritus in forest ecosystems.

Houghton, Ra, Lawrence, Kt, Hackler, Jl, & Brown, Sandra. (2001a). The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. *7*(7), 731-746.

Houghton, Ra, Lawrence, Kt, Hackler, Jl, & Brown, Sandra. (2001b). The spatial distribution of forest biomass in the Brazilian Amazon: a comparison of estimates. *Global change biology, 7*(7), 731-746.

Hügel, Stephan, & Davies, Anna (2020). Public participation, engagement, and climate change adaptation: A review of the research literature. *11*(4), e645.

IPCC. (2000a). *A special report on land-use, land-use change and forestry. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.* (0167-8809). Retrieved from

IPCC. (2000b). *A special report on land-use, land-use change and forestry. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK. (0167-8809).* (1054-9811). Retrieved from

IPCC. (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry. J. Penman, M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, F. Wagner (eds). IPCC/OECD/IEA/IGES, Hayama, Japan, pp. 580.* (1573-5095). Retrieved from

IPCC. (2006). *IPCC Guidelines for National Greenhouse Gas Inventories Volume 4. Prepared by National Greenhouse Gas Inventories Program, (Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe, K., eds.), Institute for Global Environmental Strategies (IGES) Publishing, Hayama, Japan.* (9251039550). Retrieved from

IPCC. (2007). *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report*. Retrieved from

IPCC. (2014a). *Summary for Policy Makers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Retrieved from

IPCC. (2014b). *Summary for Policy Makers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Retrieved from* Retrieved from

IPCC. (2021). *Annex VII: Glossary. In J. B. R. Matthews, V. Möller, R. van Diemen, J. S. Fuglestvedt, V. Masson-Delmotte, C. Méndez, S. Semenov, & A. Reisinger (Eds.), In climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change (pp. 2215–2256). Cambridge University Press.*: Ipcc.

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 (H.-O. Pörtner, D. C. Roberts, M. Tignor, et al., Eds.). Cambridge University Press.* (0378-1127). Retrieved from

IPCC. (2023). *Climate change synthesis, Report.* https://report.ipcc.ch/ar6syr/headline.html. Retrieved from

Jackson, Robert B, Lajtha, Kate, Crow, Susan E, Hugelius, Gustaf, Kramer, Marc G, & Piñeiro, Gervasio (2017). The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. *48*, 419-445.

Jain, Sharad K, & Kumar, Vijay. (2012a). Trend analysis of rainfall and temperature data for India. *Current science*, 37-49.

Jain, Sharad K, & Kumar, Vijay (2012b). Trend analysis of rainfall and temperature data for India. 37-49.

Janjic, Milica. (2025). The role of the International Energy Agency (IEA) in global energy governance.

Jina, Bs, Sah, Pankaj, Bhatt, Md, & Rawat, Ys. (2008). Estimating carbon sequestration rates and total carbon stockpile in degraded and non-degraded sites of Oak and Pine forest of Kumaun Central Himalaya. *Ecoprint: An International Journal of Ecology*, *15*, 75-81.

Jones, Matthew W, Peters, Glen P, Gasser, Thomas, Andrew, Robbie M, Schwingshackl, Clemens, Gütschow, Johannes, Houghton, Richard A, Friedlingstein, Pierre, Pongratz, Julia, & Le Quéré, Corinne (2023). National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *10*(1), 155.

Jose, Shibu (2009). Agroforestry for ecosystem services and environmental benefits: an overview. *76*(1), 1-10.

Jury, Mark R, & Funk, Chris (2013). Climatic trends over Ethiopia: regional signals and drivers. *33*(8), 1924-1935.

Karki, Sikha, Burton, Paul, & Mackey, Brendan (2020). Climate change adaptation by subsistence and smallholder farmers: Insights from three agro-ecological regions of Nepal. *6*(1), 1720555.

Khatri, Bishnu Bahadur, & Pasa, Rajan Binayek (2023). People's Perception on Climate Change: The Context of Local and Global Discourse. *2822*, 1613.

Kuma, Markos, & Shibru, Simon (2015). Floristic Composition, Vegetation Structure, and Regeneration Status of Woody Plant Species of Oda Forest of Humbo Carbon Project, Wolaita, Ethiopia. *2015*.

Kuyah, Shem, Dietz, Johannes, Muthuri, Catherine, Jamnadass, Ramni, Mwangi, Peter, Coe, Richard, & Neufeldt, Henry (2012). Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. *158*, 225-234.

Kent, Martin. (2011). *Vegetation description and data analysis: a practical approach*: John Wiley & Sons.

Kew, Sarah, Philip, Sjoukje, Van Oldenborgh, Geert Jan, Otto, Friederike, Haustein, Karsten, King, Andrew, Karoly, David, Zegeye, Abiy, Eshetu, Zewdu, & Hailu, Beza. (2017). *Challenges and possibilities for attribution studies in developing countries: Ethiopian drought of 2015.* Paper presented at the EGU General Assembly Conference Abstracts.

Kindu, Mengistie, Schneider, Thomas, Wassie, Alemayehu, Lemenih, Mulugeta, Teketay, Demel, & Knoke, Thomas. (2022). Ethiopian church forests and restoration options—An introduction. In *State of the art in ethiopian church forests and restoration options* (pp. 1-8): Springer.

Kothari, Chakravanti Rajagopalachari. (2004). *Research methodology: Methods and techniques*: New Age International.

Lal, Rattan (2004). Soil carbon sequestration impacts on global climate change and food security. *304*(5677), 1623-1627.

Lambert, Edward, & Deyganto, Kanbiro Orkaido (2023). The Role of Green Legacy in Promoting Sustainable Development and Combating Climate Change.

Lee, June-Yi, Marotzke, Jochem, Bala, Govindasamy, Cao, Long, Corti, Susanna, Dunne, John P, Engelbrecht, Francois, Fischer, Erich, Fyfe, John C, & Jones, Christopher. (2021). Future global climate: scenario-based projections and near-term information.

Lehtonen, Aleksi, Ťupek, Boris, Nieminen, Tiina M, Balázs, András, Anjulo, Agena, Teshome, Mindaye, Tiruneh, Yibeltal, & Alm, Jukka (2020). Soil carbon stocks in Ethiopian forests and estimations of their future development under different forest use scenarios. *31*(18), 2763-2774.

Lemenih, Mulugeta, Tolera, Motuma, & Karltun. (2008). Deforestation: Impact on soil quality, biodiversity and livelihoods in the highlands of Ethiopia. 21-39.

Lemma, Bekele, Kleja, Dan Berggren, Olsson, Mats, & Nilsson, Ingvar. (2007). Factors controlling soil organic carbon sequestration under exotic tree plantations: A case study using the CO2Fix model in southwestern Ethiopia. *Forest Ecology and Management, 252*(1-3), 124-131.

Li, Lin, Zayiti, Abudoukeremujiang, & He, Xuemin (2023). Evaluating the stand structure, carbon sequestration, oxygen release function, and carbon sink value of three artificial shrubs alongside the tarim desert highway. *14*(11), 2137.

Lovejoy, Te, & Hannah, L. (2005). Climate change and biodiversity: Yale University Press. *New Haven, Connecticut*.

Lambers, H., Chapin, F. S., & Pons, T. L. . (2008). *Plant Physiological Ecology* (Vol. 90): [Wiley, British Ecological Society].

Lohr, Sharon L. (2021). *Sampling: design and analysis*: Chapman and Hall/CRC.

Macdicken, Kenneth G. (1997). A guide to monitoring carbon storage in forestry and agroforestry projects.

Mafongoya, Pl, Nair, Pkr, & Dzowela, Bh. (1998). Mineralization of nitrogen from decomposing leaves of multipurpose trees as affected by their chemical composition. *Biology and Fertility of soils, 27*(2), 143-148.

Maja, Mengistu M, & Ayano, Samuel (2021). The impact of population growth on natural resources and farmers' capacity to adapt to climate change in low-income countries. *5*, 271-283.

Maru, Yoseph, Gebrekirstos, Aster, & Haile, Getahun (2023). Indigenous sacred forests as a tool for climate change mitigation: Lessons from Gedeo community, Southern Ethiopia. *42*(3), 260-287.

Mcsweeney, C, New, M, & Lizcano. (2008). United Nation Development Program (UNDP) ClimateChangeCountryProfilesEthiopiaAvailableathttp.

Mea, Millennium Ecosystem Assessment. (2003). Millennium ecosystem assessment.

Mebrat, Wondie (2015). Natural regeneration practice in degraded high lands of Ethiopia through area enclosure. *3*(5), 120-123.

Mehmet. (2015). Determining the bioclimatic comfort in Kastamonu City. *187*, 1-10.

Mekonen, Abebe Arega, & Berlie, Arega Bazezew (2020). Spatiotemporal variability and trends of rainfall and temperature in the Northeastern Highlands of Ethiopia. *6*, 285-300.

Mekonnen, Asersie, & Tolera, Motuma (2019). Carbon stock estimation along altitudinal gradient in Sekele-Mariam dry evergreen montane forest, North-Western Ethiopia. *8*(2), 48.

Mendoza-Poudereux, Isabel, Dziminska, Malgorzata, Pellegrini, Giuseppe, & Rowland, Jussara (2021). Climate change and public perception. Citizens' proposals for better communication and involvement. *20*(03), A09.

Mengistu, Daniel Ayalew, Bekele, Daniel Asfaw, Gela, Agumassie Genet, Meshesha, Derege Tsegaye, & Getahun, Mulatie Mekonen (2023). Woody species diversity and regeneration status of Sub-Alpine forest of Mount Adama exclosure site, Northwestern highlands of Ethiopia. *9*(6).

Millenniumecosystemassessment. (2003). Millennium ecosystem assessment.

Minwuye, Bewuketu. (2017). FARMERS'PERCEPTION AND ADAPTATION STRATEGIES TO CLIMATE CHANGE: THE CASE OF WOREILLU DISTRICT OF AMHARA REGION, NORTHEASTERN ETHIOPIA.

Mkonda, Msafiri Yusuph, He, Xinhua, & Festin, Emma Sandell (2018). Comparing smallholder farmers' perception of climate change with meteorological data: experience from seven agroecological zones of Tanzania. *10*(3), 435-452.

Mokany, Karel, Raison, R John, & Prokushkin, Anatoly (2006). Critical analysis of root: shoot ratios in terrestrial biomes. *12*(1), 84-96.

Morgan, David (2014). Pragmatism as a paradigm for social research. *20*(8), 1045-1053.

Morka, Abesh Birhanu (2025). The Threat and Ecological Benefits of Ethiopian Orthodox Tewahdo Church Forests in Ethiopia: A Review Paper. *5*(2), 21-28.

Morris, E Kathryn, Caruso, Tancredi, Buscot, François, Fischer, Markus, Hancock, Christine, Maier, Tanja S, Meiners, Torsten, Müller, Caroline, Obermaier, Elisabeth, & Prati, Daniel (2014). Choosing and using diversity indices: insights for ecological applications from the German Biodiversity Exploratories. *4*(18), 3514-3524.

Maddison, David. (2007). *The perception of and adaptation to climate change in Africa* (Vol. 4308): World Bank Publications.

Magurran, Anne E. (2003). *Measuring biological diversity*: John Wiley & Sons.

Marzouk, Osama A. (2025). *Summary of the 2023 report of TCEP (tracking clean energy progress) by the International Energy Agency (IEA), and proposed process for computing a single aggregate rating.* Paper presented at the E3S Web of Conferences.

Ministryofwater. (2016). *Ethiopian Highlands Physiography and Drainage Systems. Addis Ababa, Ethiopia.* (0167-6369). Retrieved from

MOA. (1998). Agro-ecological zones of Ethiopia. In: Ministry of Agriculture Addis Ababa.

MOA, Ministry of Agriculture. (2020). *Ethiopia's agriculture and rural development policy and strategy. Ministry of Agriculture, Federal Democratic Republic of Ethiopia.* (3030866262). Retrieved from

Montagnini, Florencia, & Nair, Pkr. (2004). Carbon sequestration: an underexploited environmental benefit of agroforestry systems. In *New vistas in agroforestry* (pp. 281-295): Springer.

Mucheye, Getie, & Yemata, Getahun (2020). Species composition, structure and regeneration status of woody plant species in a dry Afromontane forest, Northwestern Ethiopia. *6*(1), 1823607.

Mulat, Yeshambel. (2013). The role of Ethiopian Orthodox churches and monasteries in forest management practices in Chilga and Mettema woredas (districts), North Gondar zone. *2*(7), 437-446.

Munday, Callum, Washington, Richard, Engelstaedter, Sebastian, Zilli, Marcia, Harbord, Sophie, Knight, Charles, Attwood, Kitty, & Hart, Neil (2025). Southern African Climate Change: Processes, Models, and Projections. *16*(5), e70025.

Nasaandmeti. (2022). *ASTER Global Digital Elevation Model Version 3 (GDEM V3).* (1682-1750). Retrieved from

Ndondo, Joseph Tendeukai Kunashe. (2023). Review of the Food and Agriculture Organisation (FAO) strategic priorities on food safety 2023. In *Food safety-new insights*: IntechOpen.

Nmsa, National Meteorological Service Agency. (2007). *Climate Change National Adaptation Program of Action (NAPA) of Ethiopia. NMSA, Addis Ababa, Ethiopia.* . Retrieved from

Noaa. (2025). NOAA Oceanic and Atmospheric Research Ocean Carbon Observing Science Plan FY25 to FY35. In.

Ndaruzaniye, Valerie (2011). Water security in Ethiopia: Risks and vulnerabilities' assessment.

Nhamo, Luxon, Ebrahim, Girma Yimer, Mabhaudhi, Tafadzwanashe, Mpandeli, Sylvester, Magombeyi, Manuel, Chitakira, Munyaradzi, Magidi, James, & Sibanda, Mbulisi (2020). An assessment of groundwater use in irrigated agriculture using multi-spectral remote sensing. *115*, 102810.

Noor, Ahmed K, & Burton, W Scott. (1992). Computational models for high-temperature multilayered composite plates and shells.

Nyong, Anthony, Adesina, Francis, & Osman Elasha, Balgis (2007). The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *12*, 787-797.

Okonya, Joshua S, Syndikus, Katja, & Kroschel, Jürgen (2013). Farmers' perception of and coping strategies to climate change: Evidence from six agro-ecological zones of Uganda. *5*(8), 252.

Orlowska, Izabela, & Klepeis, Peter. (2018). Ethiopian church forests: a socio-religious conservation model under change. *12*(4), 674-695.

Ostrom, Elinor (2009). A general framework for analyzing sustainability of social-ecological systems. *325*(5939), 419-422.

Orindi, Victor A, & Murray, Laurel A. (2005). *Adapting to climate change in East Africa: a strategic approach*: International Institute for Environment and Development London, UK.

Palinkas, Lawrence A, Horwitz, Sarah M, Green, Carla A, Wisdom, Jennifer P, Duan, Naihua, & Hoagwood, Kimberly (2015). Purposeful sampling for qualitative data collection and analysis in mixed method implementation research. *42*(5), 533-544.

Pan, Yude, Birdsey, Richard A, Fang, Jingyun, Houghton, Richard, Kauppi, Pekka E, Kurz, Werner A, Phillips, Oliver L, Shvidenko, Anatoly, Lewis, Simon L, & Canadell, Josep (2011a). A large and persistent carbon sink in the world’s forests. *333*(6045), 988-993.

Pan, Yude, Birdsey, Richard A, Fang, Jingyun, Houghton, Richard, Kauppi, Pekka E, Kurz, Werner A, Phillips, Oliver L, Shvidenko, Anatoly, Lewis, Simon L, & Canadell, Josep G. (2011b). A large and persistent carbon sink in the world’s forests. *Science, 333*(6045), 988-993.

Paustian, Keith, Lehmann, Johannes, Ogle, Stephen, Reay, David, Robertson, G Philip, & Smith, Pete (2016). Climate-smart soils. *532*(7597), 49-57.

Parent, Guy. (2000). *Manual for woody biomass inventory*: Woody Biomass Inventory and Strategic Planning Project, Ministry of Agriculture.

Pearson, Timothy Rh. (2007). *Measurement guidelines for the sequestration of forest carbon* (Vol. 18): US Department of Agriculture, Forest Service, Northern Research Station.

Picard, Nicolas, Saint-André, Laurent, & Henry, Matieu. (2012a). *Manual for building tree volume and biomass allometric equations: from field measurement to prediction*.

Peña-Guerrero, Mayra Daniela, Senay, Gabriel B, Umirbekov, Atabek, Tarasova, Larisa, Rufin, Philippe, Pulatov, Bakhtiyor, & Müller, Daniel. (2026). Climate change has increased crop water consumption in Central Asia despite less water-intensive cropping.

Picard, Nicolas, Saint-Andre, Laurent, & Henry, Matieu. (2012). Manual for building tree volume and biomass allometric equations: from field measurement to prediction.

Picard, Nicolas, Saint-André, Laurent, & Henry, Matieu. (2012b). Manual for building tree volume and biomass allometric equations: from field measurement to prediction. *Manual for building tree volume and biomass allometric equations: from field measurement to prediction, FAO; Food and Agricultural Organization of the United Nations (2012)*.

Ramachandran, A, Jayakumar, S, Haroon, Rm, Bhaskaran, Arockiasamy, & Arockiasamy, Di. (2007). Carbon sequestration: estimation of carbon stock in natural forests using geospatial technology in the Eastern Ghats of Tamil Nadu, India. *Current science*, 323-331.

Ramachandran Nair, Pk, Mohan Kumar, B, & Nair, Vimala D. (2009). Agroforestry as a strategy for carbon sequestration. *Journal of plant nutrition and soil science, 172*(1), 10-23.

Rawashdeh, Shatha, Thneibat, Ahmad A, Aladwan, Zubeida, Taran, Ayed, & Alrababah, Abdallah (2024). Climate Changes on the Amount of Rain and Temperature from 1990-2018 in Madaba, Jordan using Geographical Information Systems. *56*(1), 82-95.

Regassa, Senait, Givey, Christina, & Castillo, Gina. (2010). The rain doesn't come on time anymore: Poverty, vulnerability, and climate variability in Ethiopia.

Reich, Peter B, Bakken, Peter, Carlson, Daren, Frelich, Lee E, Friedman, Steve K, & Grigal, David F. (2001). Influence of logging, fire, and forest type on biodiversity and productivity in southern boreal forests. *Ecology*, *82*(10), 2731-2748.

Reynolds, Travis, Sisay, Tizezew Shimekach, Wassie, Alemayehu, & Lowman. (2015). Sacred natural sites provide ecological libraries for landscape restoration and institutional models for biodiversity conservation. 1-4.

Riddle, Emily E, & Cook, Kerry (2008). Abrupt rainfall transitions over the Greater Horn of Africa: Observations and regional model simulations. *113*(D15).

Ritter, Annalena, Yaffar, Daniela, & Meier, Ina (2026). How tree diversity and ectomycorrhizal dominance affect biomass allocation of mixed deciduous forests. 2026.2001. 2029.702198.

Rohde. (2025). *Global temperature report for 2024. Berkeley Earth.* (1095-9203). Retrieved from

Rosell, Staffan. (2013). *Rainfall variability, soils and land use changes in the Ethiopian highlands*.

Ruiz, Itxaso, Faria, Sérgio H, & Neumann, Marc (2020). Climate change perception: Driving forces and their interactions. *108*, 112-120.

Saguye, Tesfaye Samuel (2017). Assessment of Farmers' Perception of Climate Change and Variability and It's Implication for Implementation of Climate-Smart Agricultural Practices: The Case of Geze Gofa District, Southern Ethiopia. *30*, 1-15.

Saha, Subhrajit K, Nair, Pk, Nair, Vimala D, & Kumar, B Mohan. (2009). Soil carbon stock in relation to plant diversity of homegardens in Kerala, India. *Agroforestry systems, 76*(1), 53-65.

Scull, Peter, Cardelús, Catherine L, Klepeis, Peter, Woods, Carrie L, Frankl, Amaury, & Nyssen, Jan (2017). The resilience of Ethiopian church forests: interpreting aerial photographs, 1938–2015. *28*(2), 450-458.

Seleshi, Yilma, & Zanke, Ulrich (2004). Recent changes in rainfall and rainy days in Ethiopia. *24*(8), 973-983.

Sen, Pranab Kumar (1968). Estimates of the regression coefficient based on Kendall's tau. *63*(324), 1379-1389.

Shahbazi, Aramesh, & Nasab, B Rezaei (2016). Carbon capture and storage (CCS) and its impacts on climate change and global warming. *7*(9).

Sharma, Yatendra, Sajjad, Haroon, Saha, Tamal Kanti, Bhuyan, Nirsobha, Sharma, Aastha, & Ahmed, Raihan (2024). Analyzing and forecasting climate variability in Nainital district, India using non-parametric methods and ensemble machine learning algorithms. 1-17.

Sheikh, Mehraj A, Kumar, Munesh, & Bussmann, Rainer W. (2009). Altitudinal variation in soil organic carbon stock in coniferous subtropical and broadleaf temperate forests in Garhwal Himalaya. *Carbon balance and management, 4*(1), 1-6.

Shibiru, Simon, & Balcha, Girma (2004). Composition, structure and regeneration status of Woody species in Dindin natural forest, southeast Ethiopia: an application for Conservation. *3*, 15-35.

Shibru, Simon, & Balcha, Girma (2004). Composition, Structure and regeneration status of woody species in Dindin Natural Forest, Southeast Ethiopia: An implication for conservation. *3*(1), 15-35.

Silver, Whendee L, & Miya, Ryan (2001). Global patterns in root decomposition: comparisons of climate and litter quality effects. *129*(3), 407-419.

Sinore, Tamrat, & Wang, Fei (2024). Impact of climate change on agriculture and adaptation strategies in Ethiopia: a meta-analysis. *10*(4).

Solomon. (2007). Contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change 2007.

Solomon. (2022). Woody species regeneration through exclosure and perception of local community on mountain Damota, Wolaita, Ethiopia. *8*, 100234.

Solomon, Susan, Qin, Dahe, Manning, Martin, Averyt, Kristen, & Marquis, Melinda. (2007). *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC* (Vol. 4): Cambridge university press.

Soromessa, & Eshete. (2021). Carbon Storage of Selected Church Forests in Northern Ethiopia: Implication for Climate Change Mitigation. Research Square (Research Square). In.

Sukhdev, Pavan, Wittmer, Heidi, Schröter-Schlaack, Christoph, Nesshöver, Carsten, Bishop, Joshua, Brink, P Ten, Gundimeda, Haripriya, Kumar, Pushpam, & Simmons, Ben. (2010). *The economics of ecosystems and biodiversity: mainstreaming the economics of nature: a synthesis of the approach, conclusions and recommendations of TEEB*: UNEP, Ginebra (Suiza).

Supriatna, Jatna. (2018). *Biodiversity Indexes: Value and evaluation purposes.* Paper presented at the E3S Web of Conferences.

Spellerberg, Ian F, & Fedor, Peter (2003). A tribute to Claude Shannon (1916–2001) and a plea for more rigorous use of species richness, species diversity and the 'Shannon–Wiener'Index. *12*(3), 177-179.

Sraku-Lartey, Margaret, Buor, Daniel, Adjei, Prince Osei-Wusu, & Foli, Ernest G %J Information Development. (2020). Perceptions and knowledge on climate change in local communities in the Offinso Municipality, Ghana. *36*(1), 16-35.

Suhaila, Jamaludin, Sayang, Mohd Deni, & Jemain, Abdul Aziz. (2008). Revised spatial weighting methods for estimation of missing rainfall data. *Asia-Pacific Journal of Atmospheric Sciences, 44*(2), 93-104.

Suryabhagavan. (2017). GIS-based climate variability and drought characterization in Ethiopia over three decades. *15*, 11-23.

Tadesse, Tsegaye. (2008). *The value of some forest ecosystem services in Ethiopia.* Paper presented at the Proceeding of a workshop on Ethiopian forestry at crossroads: the need for a strong institution. Forum for environment. Addis Ababa: Ethiopia Google Scholar.

Tashakkori, Abbas, & Teddlie, Charles. (2021). *Sage handbook of mixed methods in social & behavioral research*: SAGE publications.

Thompson, Steven K. (2012). *Sampling* (Vol. 755): John Wiley & Sons.

Tsiftsi Athanasiou, Nausika. (2025). *Assessing climate risks to global energy infrastructure.* Πανεπιστήμιο Πειραιώς,

Tura, Tulu Tolla, Argaw, Mekuria, & Eshetu, Zewdu. (2013). *Estimation of carbon stock in church forests: implications for managing church forest to help with carbon emission reduction.* Paper presented at the Climate-Smart Technologies: Integrating Renewable Energy and Energy Efficiency in Mitigation and Adaptation Responses.

Takahashi, Masamichi, Ishizuka, Shigehiro, Ugawa, Shin, Sakai, Yoshimi, Sakai, Hisao, Ono, Kenji, Hashimoto, Shoji, Matsuura, Yojiro, & Morisada, Kazuhito. (2010). Carbon stock in litter, deadwood and soil in Japan's forest sector and its comparison with carbon stock in agricultural soils. *Soil Science & Plant Nutrition, 56*(1), 19-30.

Teku, Degfie. (2025). Navigating climate uncertainty: a comprehensive review of climatic variabilities and extreme events on environmental, socio-economic, and livelihood dimensions in Ethiopia with adaptation strategies. *37*(1), 1-30.

Tesfaye, Mehari A, Gardi, Oliver, & Blaser, Jűrgen (2019). Temporal variation in species composition, diversity and regeneration status along altitudinal gradient and slope: the case of chilimo dry afromontane forest in the central highlands of Ethiopia. *138*(2), 192-224.

Tesfaye, Wondimagegn, & Seifu, Lemma (2016). Climate change perception and choice of adaptation strategies: Empirical evidence from smallholder farmers in east Ethiopia. *8*(2), 253-270.

Teshager, Zelalem, Argaw, Mekuria, & Eshete, Abeje (2018). Woody species diversity, structure and regeneration status in Weiramba forest of Amhara region, Ethiopia: implications of managing forests for biodiversity conservation. *8*(5), 16-31.

Teshome, Asaminew, & Demissie, Teferi Dejene. (2022). National Climate Outlook Forum Kiremt 2022 Impact Assessment and Bega 2022/23 Climate Impact Outlook.

Tessema, Israel, & Simane, Belay (2019). Vulnerability analysis of smallholder farmers to climate variability and change: an agro-ecological system-based approach in the Fincha'a sub-basin of the upper Blue Nile Basin of Ethiopia. *8*, 1-18.

Teutschbein, Claudia, & Seibert, Jan. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology, 456*, 12-29.

Teyso, Tefera, & Anjulo, Agena (2016). Spatio-temporal variability and trends of rainfall and temperature over Gamo Gofa zone, Ethiopia. *12*(2), 1-11.

Tilahun, Abiyou, Terefe, Hailu, & Soromessa, Teshome. (2015a). The contribution of Ethiopian Orthodox Tewahido Church in forest management and its best practices to be scaled up in North Shewa Zone of Amhara Region, Ethiopia. *Agriculture, Forestry and Fisheries, 4*(3), 123-137.

Tilahun, Abiyou, Terefe, Hailu, & Soromessa, Teshome (2015b). The contribution of Ethiopian Orthodox Tewahido Church in forest management and its best practices to be scaled up in North Shewa Zone of Amhara Region, Ethiopia. *4*(3), 123-137.

Tola, Fetene Teshome, Dadi, Diriba Korecha, Kenea, Tadesse Tujuba, & Dinku, Tufa (2025). Weather and climate services in Ethiopia: progress, challenges, and opportunities. *7*, 1551188.

Tura, Tt, Soromess, T, Argaw, Mekuria, & Leta, Seyoum. (2017). Holy hills role in biodiversity conservation and mountain management: implication of multi-purpose Ethiopian Orthodox Tewahido Church in sustainable mountain conservation. *J Biodivers Endanger Species, 5*(179), 2.

UNDP. (2007a). *Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, world population prospects: The 2006 Revision and world Urbanization prospects, 2005Revision. Available at* http://esa.un./un./unpp. Retrieved from

UNDP. (2007b). *Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, world population prospects: The 2006 Revision and world Urbanization prospects, 2005Revision. Available at* http://esa.un./un./unpp*. Retrieved from* (0140-6736). Retrieved from

UNEP. (2021). *Green Legacy initiative and forest restoration targets. United Nations Environment Programme.* Retrieved from

UNFCCC. (2007a). *Climate Change: Impacts, vulnerabilities and adaptation in the developing countries. UNFCCC secretariat. Martin-Luther-King-Strasse 853175 Bonn, Germany*. Retrieved from

UNFCCC. (2007b). *Climate Change: Impacts, vulnerabilities and adaptation in the developing countries. UNFCCC secretariat. Martin-Luther-King-Strasse 853175 Bonn, Germany. Retrieved from*. Retrieved from

UNFCCC. (2015a). *United Nations Framework Convention on Climate Change (UNFCCC) Measurements for Estimation of Carbon Stocks in Afforestation and Reforestation Project Activities under the Clean Development Mechanism: A Field Manual.* Retrieved from

UNFCCC. (2015b). *United Nations Framework Convention on Climate Change (UNFCCC) Measurements for Estimation of Carbon Stocks in Afforestation and Reforestation*

Project Activities under the Clean Development Mechanism: A Field Manual. Retrieved from (0177-798X). Retrieved from

Watson, Robert Tony, Noble, Ian R, Bolin, Bert, Ravindranath, Nh, Verardo, David J, & Dokken, David J. (2000). *Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change*: Cambridge University Press.

WBISPP. (2000). *Manual for woody biomass inventory. Woody Biomass Inventory and Strategic Planning Project, Ministry of Agriculture, Addiss Ababa, Ethiopia.* (9251039550). Retrieved from

UNICEF. (2023). The state of food security and nutrition in the world 2023.

Unmigration. (2023). International Organization for Migration (IOM).

USAID. (2009). Ethiopia livelihood zones.

Van Valkengoed, Am, Perlaviciute, Goda, & Steg, Linda (2022). Relationships between climate change perceptions and climate adaptation actions: policy support, information seeking, and behaviour. *171*(1-2), 14.

Viste, Ellen, Korecha, Diriba, & Sorteberg, Asgeir (2013). Recent drought and precipitation tendencies in Ethiopia. *112*, 535-551.
Watson, Robert Tony, Noble, Ian R, Bolin, Bert, Ravindranath, Nh, Verardo, David J, & Dokken, David J. (2000). *Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change*: Cambridge University Press.

WBISPP. (2000). *Manual for woody biomass inventory. Woody Biomass Inventory and Strategic Planning Project, Ministry of Agriculture, Addiss Ababa, Ethiopia.* (9251039550). Retrieved from
WHO. (2023). *Climate change and health.* *https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health* (1469-7769). Retrieved from

WMO. (2025). *World Meteorological Organization & United Nations Economic Commission for Africa* (2662-9984). Retrieved from

Wagesho, Negash, Goel, Narendra Kumar, & Jain, Manoj Kumar (2013). Temporal and spatial variability of annual and seasonal rainfall over Ethiopia. *58*(2), 354-373.

Wassie, Alemayehu, Sterck, Frank J, & Bongers, Frans. (2010). Species and structural diversity of church forests in a fragmented Ethiopian Highland landscape. *21*(5), 938-948.

Wassie, Alemayehu, & Teketay, Demel. (2006a). Soil seed banks in church forests of northern Ethiopia: Implications for the conservation of woody plants. *Flora-Morphology, Distribution, Functional Ecology of Plants, 201*(1), 32-43.

Wassie, Alemayehu, & Teketay, Demel (2006b). Soil seed banks in church forests of northern Ethiopia: Implications for the conservation of woody plants. *201*(1), 32-43.

Wassie, Simachew Bantigegn, Mengistu, Daniel Ayalew, & Berlie, Arega Bazezw (2022). Trends and spatiotemporal patterns of meteorological drought incidence in North Wollo, northeastern highlands of Ethiopia. *15*(12), 1158.

Woldeamlak Bewket, Woldeamlak Bewket, & Conway, D. (2007). A note on the temporal and spatial variability of rainfall in the drought-prone Amhara region of Ethiopia.

Yang, Yuanhe, Fang, Jingyun, Ji, Chengjun, & Han, Wenxuan (2009). Above-and belowground biomass allocation in Tibetan grasslands. *20*(1), 177-184.

Zegeye, Haileab, Teketay, Demel, & Kelbessa, Ensermu (2011). Diversity and regeneration status of woody species in Tara Gedam and Abebaye forests, northwestern Ethiopia. *22*, 315-328.

Zerssa, Gebeyanesh, Feyssa, Debela, Kim, Dong-Gill, & Eichler-Löbermann, Bettina (2021). Challenges of smallholder farming in Ethiopia and opportunities by adopting climate-smart agriculture. *11*(3), 192.

Appendix 1 Plant composition of the three church forests

Awuntabo	Guanesa Medahinalem	Zengebal Bedega
Scientific Name	Scientific Name	Scientific Name
Juniperus procera	Juniperus procera	Juniperus procera
Albizia gummifera	Albizia gummifera	Albizia gummifera
Maytenus arbutifolia	Maytenus arbutifolia	Maytenus arbutifolia
Olea europaea	Olea europaea	Olea europaea
Ficus thonninii Blume	Ficus thonninii Blume	Ficus thonninii Blume
Croton macrostachyus	Croton macrostachyus	Croton macrostachyus
Dodonia angustifolia	Dodonaea viscosa	Dodonaea viscosa
Erythrina abyssinica	Erythrina abyssinica	Erythrina abyssinica
Acacia polyacantha	Euphorbia abyssinica	Euphorbia abyssinica
Ficus vasta	Euphorbia tirucalli	Acacia abyssinica
Calpurnia aurea	Acacia polyacantha	Allophyllus abyssinicus
Cordia africana	Ficus vasta	Ficus vasta
Rumex nervosus	Calpurnia aurea	Calpurnia aurea
Buddleja polystachya	Cordia africana	Cordia africana
Carissa spinarum	Rumex nervosus	Rumex nervosus
Capans tomentosa	Buddleja polystachya	Buddleja polystachya
Gnttiaf llginea	Carissa spinarum	
Acacia siberana	Acokanthera schimperi	
Phoenix sp.	Capan·s tomentosa	
Ficus sur	Gn'tt·iaf 'l'llginea	
Acacia nilotica	Acacia abyssinica	
Syzigium guineense	Allophyllus abyssinicus	
Eucalvntus	Casuarina equisetifolia	
Carica papaya	Desmodium repandum	
Casuarina equisti	Diplolaphium africanum	
Cofea Arabica	Discopodiumpen	
Euclea shchimperi	Dombeya torrida	
Mangifera indica	Dovyalis verrucosa	
Clutia lanceolata	Echinops giganteus	
Rosa abyssinica Lindley	Ekebergia capensis Sparrm.	
EchinopspappiiChiov	Erianmthemum dregei	
Otostegiatomentosa	Erica arborea L.	
Acacia nilotica	Acacia nilotica	
Adhatoda schimperiana	Adhatoda schimperiana	
Bridelia micrantha	Bridelia micrantha	
Vernonia amygdalina	Vernonia amygdalina	
Vernonia bipontinnii	Vernonia bipontinnii	

Ximenia americana	Ximenia americana	
Zizyphus spina- christi	Zizyphus spina- christi	
Scolopia theifolia	Scolopia theifolia	
Rhus glutinosa Hochst		
Rhus natalensis		
Pinus patula		
Pinus radiata		
Podocarpus falcatus		
Millettia ferruginea		
Myrica salicifolia		
Myrsine africana		
Mytenus undata		

Appendix 2 Important Value Index for three church forests

Awuntabo		Guanesa Medahanialem		Zengebal Bedega	
Scientific Name	**IVI**	**Scientific Name**	**IVI**	**Scientific Name**	**IVI**
Juniperus procera	24.6961	Juniperus procera	34.23534	Juniperus procera	70.26369
Albizia gummifera	2.459284	Albizia gummifera	7.365222	Albizia gummifera	6.663424
Maytenus arbutifolia	8.061834	Maytenus arbutifolia	2.654308	Maytenus arbutifolia	20.96833
Olea europaea	11.2144	Olea europaea	24.28633	Olea europaea	43.52483
Ficus thonninii Blume	6.127527	Ficus thonninii Blume	7.657139	Ficus thonninii Blume	11.52326
Croton macrostachyus	4.654681	Croton macrostachyus	5.035144	Croton macrostachyus	25.13064
Dodonia angustifolia	1.088282	Dodonaea viscosa	0.816376	Dodonaea viscosa	5.010388
Erythrina abyssinica	0.361999	Erythrina abyssinica	1.632708	Erythrina abyssinica	6.06504
Acacia polyacantha	12.30903	Euphorbia abyssinica	0.408195	Euphorbia abyssinica	9.295835
Ficus vasta	26.31304	Euphorbia tirucalli	3.825075	Acacia abyssinica	31.6687
Calpurnia aurea	9.740322	Acacia polyacantha	0.000162	Allophyllus abyssinicus	14.48406
Cordia africana	4.814829	Ficus vasta	43.35935	Ficus vasta	15.92683
Rumex nervosus	6.750097	Calpurnia aurea	0.816327	Calpurnia aurea	10.41667
Buddleja polystachya	4.814116	Cordia africana	2.245097	Cordia africana	17.95822
Carissa spinarum	6.616392	Rumex nervosus	1.621693	Rumex nervosus	4.16667
Capans tomentosa	4.099198	Buddleja polystachya	6.636818	Buddleja polystachya	6.933415
Gnttiaf llginea	3.131976	Carissa spinarum	7.518038		
Acacia siberana	10.71485	Acokanthera schimperi	8.761381		
Phoenix sp.	4.770705	Capan·s tomentosa	7.926161		
Ficus sur	6.67745	Gn'tt·iaf 'l'llginea	12.99535		
Acacia nilotica	6.260839	Acacia abyssinica	12.55033		
Syzigium guineense	5.431112	Allophyllus abyssinicus	11.68392		
Eucalvntus	16.90271	Casuarina equisetifolia	5.135246		
Carica papaya	3.494438	Desmodium repandum	2.449064		
Casuarina equisti	4.020601	Diplolaphium africanum	2.917888		
Cofea Arabica	4.938797	Discopodiumpen	6.224413		
Euclea shchimperi	4.874915	Dombeya torrida	10.14756		
Mangifera indica	5.733255	Dovyalis verrucosa	5.102185		
Clutia lanceolata	4.468626	Echinops giganteus	6.591346		
Rosa abyssinica Lindley	3.650609	Ekebergia capensis Sparrm.	7.503007		

EchinopspappiiChiov	3.257807	Erianmthemum dregei	3.061226		
Otostegiatomentosa	3.182429	Erica arborea L.	5.066091		
Acacia nilotica	6.831006	Acacia nilotica	4.233239		
Adhatoda schimperiana	3.619125	Adhatoda schimperiana	7.253243		
Bridelia micrantha	2.172755	Bridelia micrantha	2.305655		
Vernonia amygdalina	4.443824	Vernonia amygdalina	6.270452		
Vernonia bipontinnii	4.945171	Vernonia bipontinnii	6.443681		
Ximenia americana	4.151353	Ximenia americana	6.776183		
Zizyphus spina- christi	3.643473	Zizyphus spina-christi	3.095594		
Scolopia theifolia	4.792744	Scolopia theifolia	5.393452		
Rhus glutinosa Hochst	4.49602				
Rhus natalensis	3.885019				
Pinus patula	4.744431				
Pinus radiata	3.319322				
Podocarpus falcatus	6.420354				
Millettia ferruginea	5.757316				
Myrica salicifolia	4.325095				
Myrsine africana	4.368111				
Mytenus undata	1.256983				

Appendix 3 DBH (cm), Basal area (cm)2, Relative dominances, Relative abundance, Frequency, Height (m), Percentage of species

Scientific Name	DBH(cm)	Basal area(cm)2	Relative Dominance	Relative Frequency	Relative Abundances	Total height (m)	Frequency	Percentage	I	II	III	V	VI	VII
Juniperus procera	680	363168.11	23.07	3.06	8.11	37.00	15.00	8.11	1_10	10_20	20_30	30_40	40_50	>50
Albizia gummifera	70	3848.45	0.24	3.88	3.24	11.00	6.00	3.24	6	5	5		15	
Maytenus arbutifolia	5	19.63	0.00	2.65	0.00	7.00	0.00	0.00	2	7	13		27	
Olea europapaea	310	75476.76	4.79	4.90	14.59	49.00	27.00	14.59	9	10	5		17	
Ficus thonninii Blume	250	49087.39	3.12	1.84	2.70	23.00	5.00	2.70	9	3	2		59	
Croton macrostachyus	75	4417.86	0.28	3.67	1.08	9.00	2.00	1.08	18	1	1		31.80%	
Dodonaea viscosa	1	0.79	0.00	0.82	0.00	8.00	0.00	0.00	2	26	26			
Erythrina abyssinica	1.05	0.87	0.00	1.63	0.00	7.50	0.00	0.00	2	14.6	14.6			
Euphorbia abyssinica	0.8	0.50	0.00	0.41	0.00	11.00	0.00	0.00	2					
Euphorbia tirucalli	150	17671.46	1.12	0.00	2.70	13.00	5.00	2.70	7					
Acacia polyacantha	1.8	2.54	0.00	0.00	0.00	23.00	0.00	0.00	57					
Ficus vasta	800	502654.82	31.93	2.24	9.19	50.00	17.00	9.19	30.80%					
Calpurnia aurea	0.1	0.01	0.00	0.82	0.00	3.00	0.00	0.00	I	II	III	V	VI	VII
Cordia africana	2	3.14	0.00	2.24	0.00	27.00	0.00	0.00	<10cm	1_20cm	20_30cm	30_40 cm	40_50cm	>50cm
Rumex nervosus	1.2	1.13	0.00	0.00	1.62	2.70	3.00	1.62	3					133
Buddleja polystachya	90	6361.73	0.40	2.45	3.78	14.00	7.00	3.78	9					71.90%
Carissa spinarum	1.5	1.77	0.00	2.65	4.86	8.00	9.00	4.86	9					
Acokanthera schimperi	100	7853.98	0.50	2.86	5.41	15.00	10.00	5.41	18					
Capan·s tomentosa	1.2	1.13	0.00	3.06	4.86	3.00	9.00	4.86	2					
Gn'tt·iaf 'l'llginea	2.5	4.91	0.00	3.27	9.73	9.00	18.00	9.73	2					
Acacia abyssinica	450	159043.13	10.10	2.45	0.00	37.00	0.00	0.00	9					
Allophyllus abyssinicus	270	57255.53	3.64	1.02	7.03	23.00	13.00	7.03	52					
Casuarina equisetifolia	180	25446.90	1.62	0.82	2.70	21.00	5.00	2.70						
Desmodium repandum	1.3	1.33	0.00	2.45	0.00	7.00	0.00	0.00						
Diplolaphium africanum	1.2	1.13	0.00	1.84	1.08	5.00	2.00	1.08						
Discopodiumpen	150	17671.46	1.12	5.10	0.00	15.00	0.00	0.00						

Dombeya torrida	200	31415.93	2.00	6.53	1.62	17.00	3.00	1.62						
Dovyalis verrucosa	1.7	2.27	0.00	5.10	0.00	9.00	0.00	0.00						
Echinops giganteus	1.1	0.95	0.00	5.51	1.08	5.00	2.00	1.08						
Ekebergia capensis Sparrm.	270	57255.53	3.64	2.24	1.62	23.00	3.00	1.62						
Erianmthemum dregei	0.2	0.03	0.00	3.06	0.00	6.00	0.00	0.00						
Erica arborea L.	190	28352.87	1.80	3.27	0.00	18.00	0.00	0.00						
Acacia nilotica	150	17671.46	1.12	0.41	2.70	14.00	5.00	2.70						
Adhatoda schimperiana	1.2	1.13	0.00	3.47	3.78	5.00	7.00	3.78						
Bridelia micrantha	1.3	1.33	0.00	1.22	1.08	7.00	2.00	1.08						
Vernonia amygdalina	210	34636.06	2.20	2.45	1.62	21.00	3.00	1.62						
Vernonia bipontinnii	250	49087.39	3.12	2.24	1.08	28.00	2.00	1.08						
Ximenia americana	160	20106.19	1.28	3.88	1.62	15.00	3.00	1.62						
Zizyphus spina- christi	120	11309.73	0.72	1.84	0.54	11.00	1.00	0.54						
	210	34636.06	2.20	2.65	0.54	23.00	1.00	0.54						