



**EFFECT OF SOIL EROSION ON SELECTED SOIL PROPERTIES AND
CROP PRODUCTIVITY IN CASE OF HULBARAG DISTRICT, SILTIE
ZONE CENTRAL ETHIOPIA**

BY: NEIMA JEMAL

SEPTEMBER, 2025

WERABE, ETHIOPIA

WERABE UNIVERSITY

COLLEGE OF AGRICULTURE AND NATURAL RESOURCE

DEPARTMENT OF NATURAL RESOURCE MANAGEMENT

**EFFECT OF SOIL EROSION ON SELECTED SOIL PROPERTIES AND
CROP PRODUCTIVITY IN CASE OF HULBARAG DISTRICT, SILTIE
ZONE CENTRAL ETHIOPIA**

BY: NEIMA JEMAL

MAJOR ADVISOR: SOLOMON UMER (PhD CANDIDATE)

CO-ADVISOR: HAMDU MOHAMMED (MSc.)

**THESIS SUBMITTED TO DEPARTMENT OF NATURAL RESOURCE
MANAGEMENT FOR THE PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE AWARD OF MASTERS DEGREE
WATERSHED MANAGEMENT**

SEPTEMBER, 2025

WERABE, ETHIOPIA

ADIVISORS' APPROVAL SHEET

SCHOOL OF GRADUATE STUDIES

WERABE UNIVERSITY

This is to certify that the thesis, entitled “Effect of Soil Erosion on Selected Soil Properties and Crop Productivity in Hulbarag District, Siltie Zone, Central Ethiopia Regional State” submitted to the Department of Natural Resources Management, College of Agriculture and Natural Resources Management, Werabe University, in partial fulfillment of the requirements for the award of the degree of master of science in an Watershed Management (WM) is a record of original work done by Neima Jemal during the period 2025, under my supervision and guidance and the research thesis has not formed the basis for the award of any Degree / Diploma / Associate ship / Fellowship or other similar title of any candidate of any University and it complies with the regulation and accepted standards of the university.

SOLOMON UMER (PhD candidate)

Major Advisor

Signature

Date

HAMDU MOHAMMED (MSc.)

Co – Advisor

Signature

Date

As members of the Board of Examiners of the M.Sc. Thesis open defense examination, we certify that we have read and evaluated the thesis prepared by Neima Jemal and examined the candidate. We recommend that the Thesis be accepted as it fulfilling the thesis requirements for the Degree of Master of Science in Watershed Management.

EXAMINERS' APPROVAL SHEET

SCHOOL OF GRADUATE STUDIES

WERABE UNIVERSITY

We, the undersigned, members of the Board of Examiners of the final open defense by having read and evaluated his thesis entitled “Effect of Soil Erosion on Selected Soil Properties and Crop Productivity in Hulbarag District, Siltie Zone, Central Ethiopia Regional State”, and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Masters of Science on Watershed Management.

_____	_____	_____
Name of the Chairperson	Signature	Date
_____	_____	_____
Name of Internal Examiner	Signature	Date
_____	_____	_____
Name of External examiner	Signature	Date
_____	_____	_____
SGS Approval	Signature	Date

Final approval and acceptance of the thesis is contingent upon the submission of the final copy of the thesis to the Council of Graduate Studies (CGS) through the department graduate committee (DGC) of the candidate’s major department.

BIOGRAPHICAL SKETCH

The author was born on January 20, 1985 E.C, in Arbaminch, Southern Ethiopia National Regional State, Ethiopia, from her mother, Mrs. Zenebu Yimam and father, Mr. Jemal Mohammed. She completed her primary education in Hawassa Tabor primary School. Hawassa Secondary and Preparatory School were where she completed her secondary and preparatory education, respectively. Then, in September 2014, she enrolled in Dilla University, where she earned a Bachelor of Science in Plant Science on January 24, 2014. Following graduation, she has been working as an agricultural officer and coordinator in the Natural Resources Management department of Lanfuro wereda.

In October 2023, she enrolled in Werabe University's School of Graduate Studies to go towards an MSc in Watershed Management.

DEDICATION

This thesis is dedicated to my beloved and esteemed families.

DECLARATION

I Neima Jemal hereby declare that the thesis, entitled “**Effect of Soil Erosion on Selected Soil Properties and Crop Productivity in Case of Hulbarag District, Siltie Zone Central Ethiopia**” submitted to the Department of Natural Resources Management, College of Agriculture and Natural Resources Management, Werabe University, in partial fulfillment of the requirements for the award of the Degree of Master of Watershed Management (WM) is a record of original research work done by me during 2024 – 2025, under the supervision and guidance of Solomon Umar (PhD Candidate) , and it has not formed the basis for the award of any degree / diploma / associate ship / fellowship or other similar title of any candidate of any university.

Neima Jemal

Place: Werabe University, Worabe

Date of submission: 17/ 11/2025

Signature of the Candidate

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude to Allah for ultimate support and giving endurance. I would like to say a great thanks for my main advisor, Solomon Umer (PhD Candidate), and co- advisor Hamdu Mohammed (MSc.) for their invaluable guidance, support, and encouragement throughout all activities of this research proposal. Their expertise and insightful feedback have been instrumental in shaping this study proposal.

I am sincerely grateful to College of Agriculture and Natural resources Management for providing the resources and an environment conducive to academic exploration. My heartfelt thanks also go to Siltie Zone Administration, whose financial support made this research proposal possible. In addition to the above-mentioned institutions, I would to extend my appreciation to Wachemo University and Werabe Agricultural Research Center for right hand aid in providing soil laboratories and instruments for soil test.

I would like to extend my appreciation to Mohammed Essa (PhD), Mohammed Awol (PhD), Kedrala Ahmed (PhD), Alewiya Hassen (MSc) and Henok Mesfen(MSc.) for their collaboration, assistance, and camaraderie throughout this journey. Their contributions and constructive discussions were vital in overcoming challenges.

Furthermore, I would like to say thanks my family specially my mother Zenebu Yimam, my brother Muhaba Jemal and my husband Abdulbasit Hussen for their unwavering support, patience, and understanding during the demanding moments of my research work proposal.

Finally I am sincerely grateful thanks to my friends specially Sabir Aman and his wife Leyla, Ahmed Kedir, Bamrica Gadissa, Mehdiya Hamdala and Desta Kesissa for their irreplaceable support, and encouragement throughout all activities of this thesis.

ACRONYMS AND ABBREVIATIONS

Av.P	Available Phosphorus
BD	Bulk Density
CEC	Cation Exchange Capacity
CSA	Central Statistics Agency
DA	Development Agents
Das	Development Agents (Agricultural extension workers in the Ethiopian context)
FAO	Food and Agricultural organization of United nation
FGD	Focus Group Discussion
GDP	Gross Domestic Product
GPS	Global Positioning System
MoA	Ministry of Agriculture (Ethiopian context)
OC	Organic Carbon
OSS	Observatoire du Sahara et du Sahel (Sahara and Sahel Observatory)
SPSS	Statistical Package for the Social Sciences

SWC	Soil and Water Conservation
TN	Total Nitrogen
UNEP	United Nations Environmental Program
USLE	Universal Soil Loss Equation

Table of Contents

ADVISORS' APPROVAL SHEET.....	ii
EXAMINERS' APPROVAL SHEET.....	iii
BIOGRAPHICAL SKETCH	iv
DEDICATION	v
DECLARATION	vi
ACKNOWLEDGEMENT	vii
ACRONYMS AND ABBREVIATIONS.....	viii
LIST OF TABLE	xii
LIST OF FIGURES	xiii
1. INTRODUCTION	1
1.1 Background of Study	1
1.2 Statement of the Problem.....	2
1.3 Objectives of the Study.....	2
1.3.1 General objective	2
1.3.2 Specific objectives	3
1.4 Research Questions	3
1.5 Significance of the Study	3
1.6 Organization of the Paper	3
2. LITERATURE REVIEW	5

2.1 Theoretical Literature Review	5
2.1.1 Foundational Theories of Soil Erosion and Degradation	5
2.1.2 Theoretical Linkages to Crop Productivity	5
2.1.3 Contextual Frameworks for Africa and Ethiopia	6
2.2 Empirical Literature Review	6
2.2.1 Global Evidence on Erosion Impacts	6
2.2.2 Regional Focus: Africa and Ethiopia	7
2.2.3 Synthesis and Identification of the Research Gap	7
2.3 Conceptual Framework	8
3. MATERIALS AND METHODS	9
3.1 Description of the Study Area	9
3.2 Research Design	10
3.3 Sampling Design and Techniques	10
3.4 Sample Size Determination	11
3.5 Data Types, Sources, and Collection Methods	12
3.5.1 Primary Data	12
3.5.2 Secondary Data	12
3.6 Data Analysis	12
3.7 Experimental and Survey Framework	13
3.8 Ethical Considerations	14

4. RESULTS AND DESCUSSION.....	15
4.1 Demographic characteristics of households (Continuous Variables)	15
4.2 Demographic characteristics of Respondents (Categorical Variables)	15
4.3 Farming Practices of household Farmers in the Study area.....	17
4.4 Yield Trends of Main Crop production and productivity in the Study area.....	19
4.5 Challenges of Crop Productivity and Soil erosion.....	20
4.6 The Main Effect of Slope Gradient and Conservation Practices on Soil Physical Properties	23
4.6.1. Soil Texture.....	23
4.6.2. Bulk Density and Soil Moisture Content	24
4.7. The Effect of Interaction between Slope and Conservation Practices on Soil Physical Properties	25
4.8. The Effects of Slope Steepness and Soil Conservation Techniques on Soil Chemical Properties	27
4.8.1. Soil Reaction (pH), Salinity (EC), and Nutrient Retention Capacity (CEC).....	29
4.8.2. Soil Organic Carbon (OC), Total Nitrogen (TN), and Available Phosphorus (AvP)....	30
4.8.3. The Interaction Effect of Slope Steepness and Conservation Practice on Available Phosphorus (AvP)	31
4.9. Regression Analysis	33
5. CONCLUSION AND RECOMMENDATIONS	35
5.1. Conclusion	35
5.2. Recommendations	36
REFERENCES	38

APPENDICES	45
------------------	----

LIST OF TABLE

Table 1 Conceptual framework for soil erosion	27
Table 2, Data Collection Framework for Soil Analysis and Farmer Survey	34
Table 3 : Descriptive Statistics of Socioeconomic Characteristics (Continuous Variables).....	36
Table 4 Distribution of Educational Attainment and Gender among Respondents.....	37
Table 5 .Distribution of Cropping Patterns and Land Management Practices among Respondents	38
Table 6 Decadal Trends in Crop Yields and Production Changes among Respondents	40
Table 7 Farmers Knowledge of Soil Erosion Causes, Impacts, and Adoption Constraints.....	42
Table 8 : Soil Physical Properties as Influenced by Slope Steepness and Conservation Practice.....	48
Table 9 : Soil Chemical Properties as Influenced by the main effect of Slope Steepness.....	52
Table 10: Interaction Effect of Slope Steepness and Conservation Practice on Available Phosphorus (AvP)	57
Table 11 Results of Multiple Linear Regression Analysis for Factors Influencing Maize Yield (qt/ha) in Hulbarag District.....	60

LIST OF FIGURES

Figure 1. Diagrammatic Conceptual framework.....	5
Figure 2. Map of the study area.....	10

Abstract

In Ethiopia, soil erosion is still a significant agricultural and environmental problem that has a significant influence on crop yields, livelihoods, and soil fertility. In the Hulbarag District of the Siltie Zone, Central Ethiopia, this study examined the effects of soil erosion on specific soil physicochemical properties and agricultural output. Field soil collection, laboratory testing, and household questionnaires were all integrated into a mixed-methods approach. In order to determine the three levels of erosion severity (low, moderate, and severe), 18 combined soil samples were collected from fields, and 268 families were surveyed using standardized questionnaires. Descriptive statistics, Analysis of Variance, and regression methods were utilized for data analysis in SPSS. The findings indicated that both slope gradient and soil conservation methods had a notable impact on soil physical and chemical characteristics. Steeper slopes showed increased bulk density (1.38 g/cm^3) and reduced organic carbon (1.8%) and available phosphorus (10.22 ppm), signifying significant nutrient depletion. In comparison, plots featuring soil and water conservation structures, especially bunds combined with grass strips, exhibited better soil texture, reduced compaction, increased moisture levels (22%), and improved fertility measures, including organic carbon (2.6%), total nitrogen (0.22%), and available phosphorus (15.5 ppm). Farmers engaging in conservation also indicated increased and more consistent crop yields, especially for maize and Teff. The research finds that soil erosion negatively impacts soil characteristics and diminishes crop yields, whereas combined physical and biological soil and water conservation methods successfully rejuvenate soil quality and improve production. It advises encouraging conservation strategies tailored to specific sites, educating farmers, and implementing integrated land management practices to maintain agricultural productivity and environmental stability in the Hulbarag District and comparable agro-ecological areas.

Key words: Conservation practices, Soil erosion, Soil fertility, Hulbarag District

CHAPTER ONE

1. INTRODUCTION

1.1 Background of Study

Soil erosion is one of the most serious environmental problems affecting agricultural productivity, water quality, and ecosystem stability worldwide. It occurs when soil particles are detached and transported by agents such as water, wind, or gravity (Kefyalew *et al.*, 2021). The process leads to the removal of the fertile top soil layer, which contains essential nutrients and organic matter required for plant growth. As a result, soil erosion significantly reduces soil fertility, disrupts soil structure, and diminishes the capacity of land to support sustainable crop production. Globally, land degradation caused by soil erosion has become a major threat to food security, natural resource sustainability, and environmental health (Adimassu *et al.*, 2014). In many regions of the world, particularly in developing countries where agriculture is the primary source of livelihood, soil erosion continues to undermine agricultural productivity and rural livelihoods.

Sub-Saharan Africa is among the regions most severely affected by soil erosion and land degradation. Rapid population growth, deforestation, overgrazing, and unsustainable land management practices have intensified soil degradation across the continent (UNEP, 2021). These pressures have accelerated the rate of soil loss and reduced the productive capacity of agricultural lands. It is estimated that approximately 30 billion tons of fertile soil are lost globally each year due to erosion, with a significant proportion occurring in Africa (Bouteska *et al.*, 2024). The loss of productive soil not only reduces crop yields but also contributes to declining soil fertility, increased sedimentation in water bodies, and reduced agricultural sustainability. Consequently, soil erosion has become one of the major environmental challenges threatening food security and economic development in many African countries.

Ethiopia is among the countries most seriously affected by soil erosion due to its rugged topography, intense rainfall patterns, high population density, and long history of agricultural land use. The Ethiopian highlands, which support the majority of the country's agricultural production, are particularly vulnerable to soil erosion. Studies indicate that these highland areas lose about 1.5

billion tons of fertile topsoil annually due to water erosion (Pimentel & Burgess, 2013). This massive soil loss results in declining soil fertility, reduced agricultural productivity, and increased land degradation. In addition, the rapid population growth in Ethiopia has increased pressure on limited land resources, forcing farmers to cultivate marginal lands and steep slopes that are highly susceptible to erosion. As a result, land degradation has become a critical challenge affecting agricultural sustainability and rural livelihoods in the country.

Agriculture plays a vital role in Ethiopia's economy and livelihood systems. The sector supports the majority of the rural population and contributes significantly to the national economy. According to the Ministry of Agriculture (MoA, 2021), agriculture contributes more than one-third of the national gross domestic product (GDP), provides nearly three-quarters of employment opportunities, and accounts for a substantial portion of the country's foreign exchange earnings. Most agricultural production in Ethiopia occurs in the highland regions, which account for approximately 90% of the country's total crop production (Zerssa *et al.*, 2021). However, the sustainability of agricultural production in these areas is increasingly threatened by soil erosion and land degradation.

In many parts of Ethiopia, continuous cultivation, deforestation, overgrazing, and limited soil and water conservation practices have accelerated soil erosion processes. The removal of vegetation cover and improper land management practices expose soil surfaces to rainfall and runoff, increasing the rate of soil loss. When the fertile topsoil layer is removed, essential soil nutrients and organic matter are also lost, which leads to declining soil fertility and reduced crop yields. This degradation of soil resources threatens the long-term sustainability of agricultural production and food security in the country.

The problem of soil erosion is particularly severe in the southern and central highlands of Ethiopia, where steep slopes, high rainfall intensity, and increasing population pressure contribute to land degradation. The Siltie Zone, located in the Southern Ethiopia region, is one of the areas where agricultural lands are highly vulnerable to soil erosion. Within this zone, Hulbarag District is characterized by steep topography, variable rainfall patterns, and intensive land use practices, which increase the susceptibility of soils to erosion. Farmers in the area depend mainly on small-scale rain-fed agriculture for their livelihoods, making them highly vulnerable to the negative impacts of soil degradation.

Soil erosion in Hulbarag District has resulted in the loss of fertile topsoil, depletion of soil nutrients, and reduction of soil organic matter, which ultimately affects crop productivity. Declining soil fertility and reduced agricultural output have placed additional pressure on local farming communities that rely heavily on agricultural production for food and income. Therefore, understanding the extent to which soil erosion affects soil properties and crop productivity is essential for developing appropriate land management and soil conservation strategies in the area.

1.2 Statement of the Problem

Land degradation, particularly soil erosion, is one of the most serious environmental challenges affecting agricultural productivity in many developing countries. In rural areas where livelihoods largely depend on rain-fed agriculture, the deterioration of soil resources directly threatens food security and economic stability (FAO, 2019).

In sub-Saharan Africa, soil erosion is considered the leading cause of declining soil fertility and reduced agricultural productivity (Mani *et al.*, 2021). Inadequate soil and water conservation practices, especially in densely populated and ecologically fragile landscapes, have accelerated land degradation, resulting in declining crop yields, increased food insecurity, and worsening rural poverty (Tanto & Laekemariam, 2019).

Estimates suggest that agricultural productivity in Africa could decline by up to 50% due to land degradation and desertification (OSS, 2024), while historical analyses indicate yield reductions ranging from 2% to 40%, with an average loss of about 8.2% across the continent (Bouteska *et al.*, 2024).

Ethiopia is among the countries most severely affected by soil erosion due to its rugged topography, high population pressure, and intensive land use practices. A large proportion of the population relies on agriculture for their livelihood, which increases pressure on limited land resources (Etsay *et al.*, 2023).

Studies indicate that cultivated lands in Ethiopia lose an average of up to 42 t ha⁻¹ yr⁻¹ of soil, significantly higher than losses from grazing lands, which average about 5 t ha⁻¹ yr⁻¹ (Hurni *et al.*,

2020). Unsustainable farming practices such as continuous cultivation, overgrazing, deforestation, and limited soil conservation measures further accelerate soil degradation (Teku & Derbib, 2024).

In the central and southern highlands, including areas such as Kambata, Hadiya, Gurage, Alaba, and Siltie, steep slopes combined with high population density intensify soil erosion risks (Waktola, 2020). The removal of the fertile topsoil layer, which contains most of the essential nutrients and organic matter required for plant growth, results in deterioration of soil physical, chemical, and biological properties, ultimately reducing crop productivity.

Although numerous studies have documented the general extent and impacts of soil erosion in Ethiopia, most of them focus on estimating soil loss rates or evaluating conservation practices at regional or watershed scales.

However, limited empirical studies have specifically quantified how soil erosion alters key soil properties; such as soil organic carbon, nutrient availability, bulk density, and soil moisture and how these changes directly affect crop productivity at the local farm level.

This knowledge gap is particularly evident in the Silte Zone, where agricultural lands are increasingly exposed to soil erosion due to steep slopes, deforestation, continuous cultivation, and insufficient soil and water conservation practices.

In the Hulbarag District of the Silte Zone, farmers frequently report declining soil fertility and reduced crop yields of major staple crops such as teff, wheat, and maize. Despite these observations, there is a lack of detailed scientific evidence linking soil erosion severity with changes in soil physical and chemical properties and their subsequent effects on crop productivity in the area. The absence of such localized data limits the ability of policymakers, extension workers, and farmers to design effective, site-specific soil management and conservation strategies.

Therefore, investigating the effects of soil erosion on soil properties and crop productivity in Hulbarag District is essential to generate empirical evidence that can support sustainable land management and improve agricultural productivity in the region. Understanding these relationships will help identify the extent to which soil degradation contributes to declining crop yields and provide a scientific basis for developing targeted soil conservation and land management practices.

1.3 Objectives of the Study

1.3.1 General objective

This research aims to assess the effects of soil erosion on selected soil properties and crop productivity in Hulbarag District, Siltie Zone, Central Ethiopia Regional State.

1.3.2 Specific objectives

- ✚ To identify the major socio-economic and biophysical factors influencing soil erosion severity in the study area
- ✚ To evaluate the effects of soil erosion on soil physicochemical properties
- ✚ To examine the effects of soil erosion on crop productivity

1.4 Research Questions

- ✚ How does soil erosion affect soil physicochemical properties in Hulbarag District?
- ✚ What are the key socio-economic and biophysical factors influencing soil erosion severity and its impacts on soil properties and crop production?
- ✚ What are the measurable effects of soil erosion on crop productivity in the study area?

1.5 Significance of the Study

Understanding the causes of soil erosion is vital for effective land management and making informed decisions about land use. This research explores the relationship between soil erosion and crop performance, highlighting its economic implications, especially in regions where agriculture is a key livelihood. The findings will support the development of sound policies aimed at soil protection and the promotion of sustainable agriculture.

Agricultural extension workers will benefit from this study by gaining insights to provide better guidance on practices such as contour farming, agroforestry, and crop diversification. Farmers will receive practical knowledge about the consequences of soil erosion and the advantages of proper land management. Additionally, the study will suggest straightforward erosion control methods, including increased tree planting and improved farming techniques.

1.6 Organization of the Paper

The research paper broke down into five sections. First up, chapter one laid out where the topic came from, what issues it tackled, the goals, why it mattered, along with how far it reached. Moving on, chapter

two covered past writings tied to the work - starting off with core theories before shifting into real-world findings. That leads to chapter three presents how the study was set up - alongside ways used to gather info, plus techniques for breaking it down and making sense of it. Chapter four covers what showed up in the data, showing patterns while explaining their meaning. In chapter five, outcomes from the work come into focus, followed by talks built around those discoveries. The last part dives into wrapping things up, offering suggestions drawn straight from what turned up during the search.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Theoretical Literature Review

This section presents the main theoretical models and concepts that underpin the understanding of soil erosion processes, their effects on soil ecosystems, and the resulting impact on agricultural productivity.

2.1.1 Foundational Theories of Soil Erosion and Degradation

The foundational theory of soil erosion was largely developed by Bennett (1939), who emphasized that topsoil is the key source of soil fertility and advocated for preventive conservation measures. Contemporary frameworks have broadened this perspective by introducing the idea of ecosystem services, viewing soil as a form of natural capital that delivers essential functions such as nutrient cycling, water regulation, and supporting agricultural production (Pori et al., 2022). This approach aligns with sustainable land management strategies aimed at harmonizing human activities with natural systems to reduce degradation (Ayesu & Gyabaah, 2014).

From a soil science standpoint, erosion is understood to trigger a chain reaction of degradation. The Soil Disorder Theory suggests that erosion damages soil structure, leading to decreased porosity, lower infiltration rates, and diminished water retention (Tamfuh et al., 2018). Additionally, the selective loss of fine particles and organic matter not only reduces nutrient levels but also speeds up nutrient leaching, causing a decline in the soil's overall chemical fertility (Lal, 2001).

2.1.2 Theoretical Linkages to Crop Productivity

Several agronomic principles explain how soil erosion affects crop yields. Liebig's Law of the Minimum states that the loss of even one essential nutrient due to erosion can limit crop production, regardless of other favorable conditions. Meanwhile, models of soil-plant-water interactions demonstrate that degraded soils with reduced water-holding capacity impose both water stress and physical constraints on root growth, thereby restricting plant development (Hillel, 2004). The Threshold Model Theory (Stocking, 2003) issues a critical caution: when soil depth and fertility drop below a certain critical threshold, crop

yields may decline irreversibly, potentially pushing agricultural systems beyond the point where recovery is economically viable.

2.1.3 Contextual Frameworks for Africa and Ethiopia

Theoretical models tailored to the African context often highlight the region's specific vulnerabilities. The Fragile Ecosystem Theory points to the harmful combination of naturally thin tropical topsoils, heavy seasonal rains, and human pressures, which together intensify land degradation (Synthesis et al., 2005). This is further exacerbated by the Nutrient Depletion Framework (Sanchez, 2002), which notes that erosion in tropical areas disproportionately removes limited nitrogen and phosphorus, key nutrients that restrict plant growth.

In Ethiopia, the Highland Erosion Theory identifies the interaction of steep slopes, erosive rainfall, and widespread farming on fragile soils as the main cause of severe soil loss (Worku & Tripathi, 2015). This has led to the Yield Gap Theory, which explains the large disparity between potential and actual crop yields partly as a result of erosion-driven soil degradation. Lastly, the Sustainability Threshold Theory (Tadesse & Abebe, 2014) warns that ongoing erosion without effective intervention could push Ethiopian agriculture past an ecological tipping point, with serious consequences for the country's food security.

This section outlines the key theoretical models and concepts that form the foundation for understanding soil erosion processes, their impact on soil ecosystems, and their consequent effects on agricultural productivity.

2.2 Empirical Literature Review

This section summarizes findings from recent empirical research, examining global and regional patterns and highlighting key knowledge gaps relevant to Ethiopia.

2.2.1 Global Evidence on Erosion Impacts

Empirical research consistently measures the significant global impact of soil erosion. Borrelli et al. (2020) report a concerning rise in global soil erosion rates by 2.5 billion tons per year over recent decades, which directly causes losses of soil organic carbon and nutrients. A major meta-analysis by Bakker et al. (2021) confirmed these effects, showing an average crop yield reduction of 13.4% across different crops

and regions due to the loss of topsoil. However, the severity of these impacts varies. For example, Phuong *et al.* (2024) found substantial yield decreases of 15-30% for rice in Southeast Asia, while data from Sub-Saharan Africa show more variability. This difference is likely due to variations in socio-economic capacity for erosion control, the types of crops cultivated, and the natural resilience of local soils.

2.2.2 Regional Focus: Africa and Ethiopia

In Africa, the empirical data confirms extensive nutrient mining via erosion. Tully *et al.* (2015) quantified annual median losses of 22 kg N, 2.5 kg P, and 15 kg K per hectare in Sub-Saharan Africa, a depletion rate that far outstrips inputs in many smallholder systems. The direct consequence for food production is clear: research by Tamene *et al.* (2017) attributes 8% to 21% of the yield decline for staple crops like maize and sorghum in East Africa directly to soil erosion.

Ethiopia presents a case study of some of the most severe erosion rates globally. Studies, such as that by Tsegaye (2019), document annual soil losses ranging from 20 to an extreme of 300 tons per hectare in the highlands, leading to corresponding declines in soil depth, organic matter, and nutrient levels. The impact on productivity is direct and significant, with Tadesse *et al.* (2017) linking erosion to annual grain yield reductions of 10-25% in highly affected areas, thereby exacerbating food insecurity (Yagaso *et al.*, 2024).

2.2.3 Synthesis and Identification of the Research Gap

A thorough review of the empirical literature shows that although the harmful effects of soil erosion are well documented globally and within Ethiopia, these impacts are highly specific to particular locations. The success of mitigation measures, such as improved soil quality and increased yields observed with soil and water conservation (SWC) practices in Korekore (Tanto & Laekemariam, 2019) or the use of Fanya Juu terraces (Kassawmar *et al.*, 2018), depends on local environmental and socio-economic conditions. Therefore, there is a notable gap in knowledge regarding the exact erosion rates, their specific effects on soil properties, and the resulting yield losses in the Hulbarag District. This study aims to provide this localized empirical data, which is essential for developing targeted and effective conservation strategies.

2.3 Conceptual Framework

Drawing on the reviewed literature, the following conceptual framework (Figure 1) was created to guide this research. It illustrates the proposed relationships between driving factors, the process of erosion, its consequences, and potential mitigating interventions.

The framework suggests that soil erosion, the independent variable, is influenced by several erosion drivers: rainfall erosivity, soil erodibility, and the slope's gradient and length. The main consequence of soil erosion is soil degradation, which serves as the mediating variable. This degradation appears as a reduction in soil depth, a decrease in organic matter, and lower nutrient levels (nitrogen, phosphorus, potassium), all of which negatively affect the soil's physical properties, such as its structure and water retention capacity.

These deteriorated soil properties directly cause a decline in crop productivity, the study's dependent variable. The strength of this relationship is influenced by two main groups of factors:

1. Socio-economic context: including farmers' education, their access to capital for soil and water conservation (SWC), and local cultural attitudes toward conservation.
2. Management interventions: such as the use of physical SWC measures (like terraces) and agronomic practices (such as adding organic matter) that help reduce erosion and enhance soil health.

This framework emphasizes the importance of not only measuring the direct impacts of erosion but also understanding the local socio-economic conditions and management practices that affect the entire system.

Table 1 Conceptual framework for soil erosion

Component	Elements	Impact
Erosion Drivers	Rainfall, Soil type, Slope	Causes initial soil loss
Soil Degradation	Loss of depth, Organic matter, Nutrients	Reduces soil fertility
Crop Impact	Reduced yields, Poor quality	Lowers farm productivity

Interventions	SWC practices, Soil amendments	Mitigates erosion
Socio-economic	Education, Funding, Culture	Influences success

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Description of the Study Area

The Hulbarag district is situated in the Siltie Zone of Central Ethiopia, about 188 km from Addis Ababa and 10 km from the zonal capital, Werabe. It is located between latitudes 7°45'42" and 8°05'11" N, and longitudes 38°46'41" and 39°07'12" E. The district features an agricultural-based economy and diverse terrain, including rugged highlands, mid-altitude areas, and gentle lowlands. According to projections by the Central Statistical Agency (CSA, 2024), the population stands at 86,598, with 18,308 households.

Covering roughly 40,300 hectares, the land includes 19,174 hectares under cultivation, 5,728 hectares of forest, and 2,942 hectares covered by bushes and shrubs. Elevations range from 1,891 to 2,000 meters above sea level, resulting in varied microclimates. The district experiences two rainy seasons: the main Kiremt season from June to September and a shorter Belg season. Annual rainfall averages between 900 mm and 1,200 mm, while average temperatures range from 15°C to 25°C.

The predominant soils are Nitisols and Cambisols, which are moderately fertile but prone to erosion due to their high clay content and the area's steep slopes. Smallholder farming is the main livelihood, with major crops including teff (*Eragrostis tef*), maize (*Zea mays*), and wheat (*Triticum* spp.). Traditional farming methods, such as plowing uphill and limited crop rotation, contribute to soil erosion and land degradation. Although soil and water conservation techniques like Fanya Juu terraces and stone bunds have been introduced, their use is inconsistent because of financial limitations and lack of awareness (Hulbarag Agricultural Office, 2024).

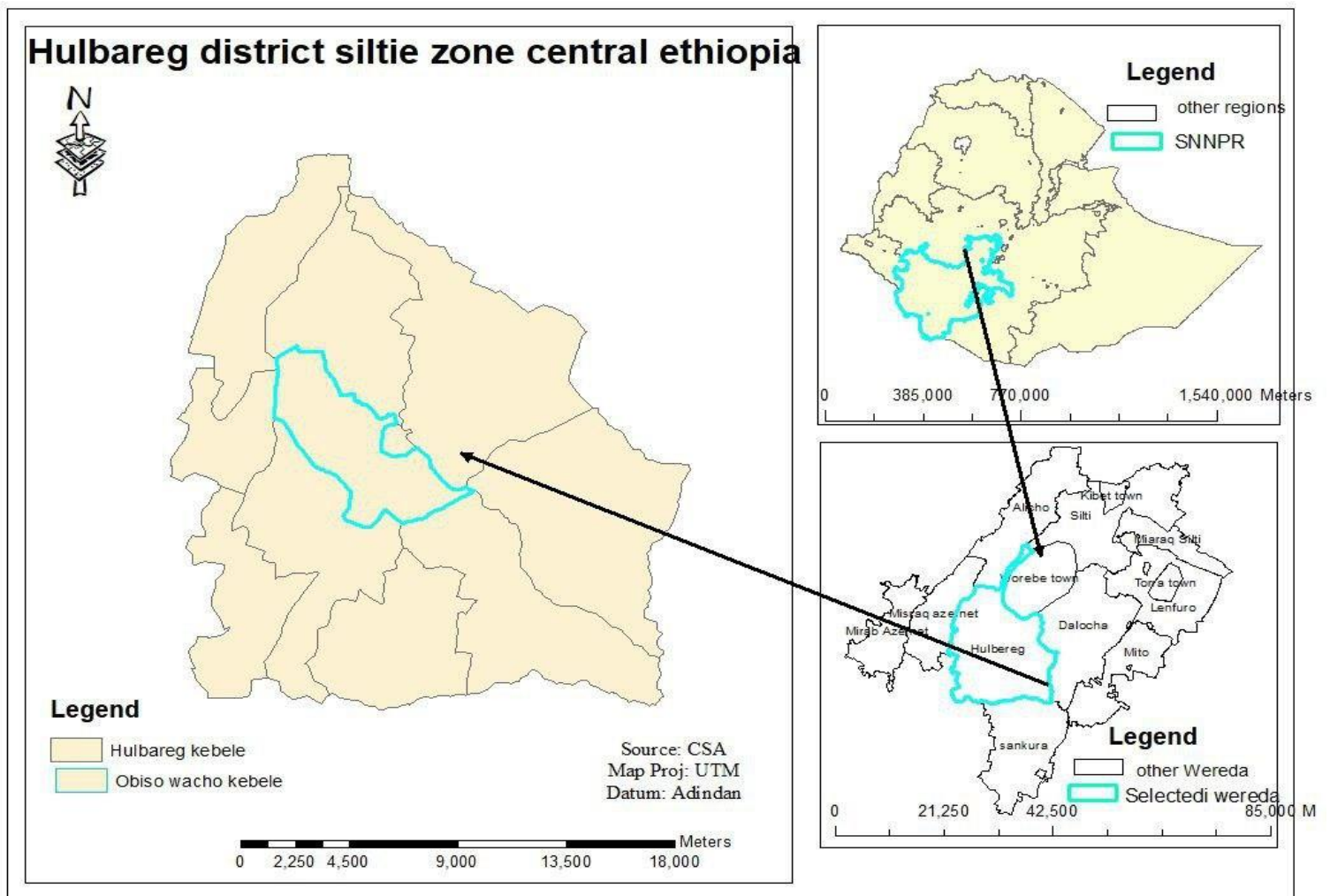


Figure 1. Map of the study area

3.2 Research Design

This study employed a mixed-methods research design, specifically using a descriptive survey design for the quantitative component and a case study design for the qualitative component, to collect and analyze both numerical and narrative data. The quantitative part included soil sampling and laboratory testing to objectively evaluate how erosion affects soil characteristics, along with a farmer survey to gather perceptions about its impact on crop yields. The qualitative aspect involved focus group discussions (FGDs), which added contextual understanding and helped validate the quantitative results. This approach was chosen to thoroughly address both the physical and socio-economic aspects of soil erosion in the study area.

3.3 Sampling Design and Techniques

A multi-stage sampling strategy was applied. Initially, the Wacho Abeso kebele was purposefully selected from the district's 11 kebeles based on information from the Hulbarag Agricultural Office (2023), which identified it as one of the most severely eroded areas. This ensured the study concentrated on a location where erosion effects were significant and relevant.

Within Wacho Abeso, the sampling frame included 812 household heads. Farmland was categorized into three erosion severity levels (Low, Moderate, Severe) using expert evaluations and local knowledge. Two sampling methods were then used simultaneously:

1. For Soil Sampling: 18 composite soil samples were collected, with 6 samples taken randomly from each erosion severity category.
2. For the Farmer Survey: A stratified random sampling method was employed to select farmers for interviews.

3.3.1.1 Sample Size Determination

Soil Samples: As described above, 18 composite samples (6 from each of the 3 erosion severity levels) were deemed sufficient for comparative statistical analysis. **Farmer Survey:** The sample size for the household survey was calculated using the Yamane (1967) formula for a finite population, with a 95% confidence level and a margin of error (e) of 5%.

$$n = N / (1 + N(e)^2)$$

$$n = N / (1 + 812(0.05)^2)$$

$$n = N / (812 / 1 + 812 * (0.0025)^2)$$

$$n = N / (812 / 1 + 812 * (2.03))$$

$$n = 812 / 3.03$$

$$n = 268$$

Therefore, the calculated sample size was 268 household heads. These were proportionally allocated to the three erosion severity strata based on the number of households in each.

3.4 Data Types, Sources, and Collection Methods

3.4.1 Primary Data

Soil Data: Composite topsoil samples (0-20 cm depth) were gathered from 18 selected fields following a zigzag sampling pattern. The samples were air-dried, sieved through a 2 mm mesh, and analyzed at the Werabe Soil Laboratory for various properties including texture (using the hydrometer method), bulk density (core method), soil pH (potentiometric method), organic carbon (Walkley-Black method), total nitrogen (Kjeldahl method), available phosphorus (Bray II method), and cation exchange capacity (ammonium acetate method).

- **Farmer Survey Data:** A structured questionnaire was administered to 268 households to collect information on demographic details, farming practices, and self-reported yields of teff, maize, and wheat during the 2024 meher season.

- **Qualitative Data:** Two Focus Group Discussions (FGDs), each comprising six participants (including elders, female farmers, youth, and local leaders), were held to gain insights into local views on soil erosion, its impacts, and the difficulties faced in adopting conservation measures.

3.4.2 Secondary Data

Secondary data were obtained from published research articles, books, and unpublished materials from the Hulbarag district agricultural office, such as land use maps and project reports.

3.5 Data Analysis

Quantitative data were analyzed using IBM SPSS Statistics. Both descriptive and inferential statistical techniques were employed to examine the relationships between soil erosion severity, soil physicochemical properties, and crop productivity.

Soil Data Analysis:

Descriptive statistics, including means and standard deviations, were computed for all measured soil physicochemical properties such as soil organic matter, total nitrogen, available phosphorus, pH, and cation exchange capacity. To examine the effect of soil erosion on these soil properties, multiple linear regression analysis (Ordinary Least Squares, OLS) was applied. In this analysis, soil erosion severity, measured as a continuous variable (e.g., estimated soil loss in tons per hectare per year using the Revised Universal Soil Loss Equation), was treated as the independent variable, while soil physicochemical properties were treated as dependent variables. This regression approach allowed for evaluating the magnitude and direction of the relationship between erosion severity and soil quality indicators, providing a stronger analytical framework than simple mean comparison.

Crop Productivity Analysis:

The impact of soil erosion on crop productivity was also assessed using multiple linear regression models, where crop yield served as the dependent variable and erosion severity was included as the key explanatory variable. This approach enabled quantification of the extent to which increasing soil erosion contributes to changes in crop yield while allowing for the inclusion of additional explanatory variables where necessary.

Farmer Survey Data:

Socio-economic and farm management characteristics of households were summarized using descriptive statistics such as frequencies, percentages, and means. Where appropriate, regression analysis was also used to explore relationships between socio-economic factors (e.g., land management practices, education level, and conservation measures) and erosion severity.

Qualitative Data Analysis:

Qualitative data collected from focus group discussions (FGDs) were analyzed using thematic analysis. Responses were coded and categorized to identify major themes related to farmers' perceptions of the causes of soil erosion, its impacts on soil fertility and crop production, and potential soil and water conservation strategies.

3.6 Experimental and Survey Framework

The following table outlines the data collection design, distinctly separating the soil sampling (experimental) aspect from the farmer survey component.

Table 2, Data Collection Framework for Soil Analysis and Farmer Survey

Component	Factor / Focus	Levels / Strata	Replication / Sample Size	Data Collection Method
Soil Sampling & Analysis	Erosion Severity	1. Low Erosion 2. Moderate Erosion 3. Severe Erosion	6 fields per level (18 composite samples total)	Soil sampling (0-20 cm depth). Laboratory analysis of physical (texture, BD) and chemical properties (pH, OC, TN, Av.P, CEC).

Farmer Survey	Crop Productivity & Practices	Households stratified by the erosion level of their farm: 1. Low Erosion 2. Moderate Erosion 3. Severe Erosion	268 households total (allocated proportionally per stratum)	Structured questionnaires to collect data on: • Socio-economic characteristics • Farming practices • Self-reported yield (teff, maize, wheat) for 2024 season.
Qualitative Data	Local Perceptions & Context	N/A	2 FGDs (12 participants total)	Focus group discussion guides to explore perceptions, challenges, and local knowledge.

3.7 Ethical Considerations

This study strictly followed ethical guidelines to protect the privacy, confidentiality, and dignity of the participants. Initially, participants were informed about the study's objectives, the types of data to be collected, and how the data would be used. Participation was voluntary, and respondents had the right to withdraw from the study at any time without any repercussions.

No personal or identifying information was recorded or disclosed to maintain participants' privacy and security. All data collected was anonymized, with sensitive information such as names and contact details excluded from the report. The data was securely stored and used exclusively for the purposes of this academic research. Upon completion of the study, the data will not be shared with or transferred to any third parties, ensuring its confidentiality. Efforts were made to respect the cultural, social, and personal values of the participants throughout the research process. The questions were carefully designed to avoid causing any discomfort or harm. Before starting the study, the data collection questionnaire was reviewed by advisors and colleagues to ensure it met established ethical standards.

CHAPTER FOUR

4. RESULTS AND DESCUSSION

4.1 Demographic characteristics of households (Continuous Variables)

Household Age: The table below indicates that the youngest household head was 34 years old, the oldest was 51 years old, and the average age of household heads in the study area is 42.44 years.

Household Family Size: According to the table, the smallest family size in the study area is 4 members, the largest family size is 7 members, and the average family size is 5.72 members.

Land Holding Size: The table shows that the smallest land holding size among households in the study area is 0.75 hectares, the largest is 2 hectares, and the average land holding size is 1.33 hectares.

Table 3 : Descriptive Statistics of Socioeconomic Characteristics (Continuous Variables)

Variable	Sample Size (N)	Minimum	Maximum	Mean $\pm$ SD
Age of household head (years)	268	34	51	42.4 $\pm$ 3.2
Household size (number of members)	268	4	7	5.7 $\pm$ 0.8
Land holding size (hectares)	268	0.75	2	1.34 $\pm$ 0.28

Note: Data collected from household surveys conducted in Hulbarag District, 2025.

4.2 Demographic characteristics of Respondents (Categorical Variables)

Education Level: The educational background of the respondents reveals that the majority, 51.7% (138.6 individuals), have not received any formal education. Those with primary education make up 41.5% (111.2 individuals), while a smaller group, 6.8% (18.2 individuals), have completed secondary education. Importantly, none of the participants have attained college-level education or higher. This suggests that formal education is generally limited within the study group, with more than half lacking any formal schooling. The analysis shows that a significant portion, 51.7% (n = 138.6), have no formal education, 41.5% (n = 111.2) have completed primary school, and only 6.8% (n = 18.2) have secondary education. Notably, no respondents reported tertiary or higher education. These results indicate a relatively low level of formal education among the participants, which could affect their ability to adopt new technologies and engage in development initiatives.

Household Gender: The gender composition of the respondents is heavily skewed toward males, who make up 90.8% (n = 243.3) of the sample, while females represent just 9.2% (n = 24.7). This significant gender imbalance points to a predominantly male population in the study, which may influence gender-inclusive involvement and decision-making within the context examined. The demographic data show a strong male majority, with males comprising 90.8% (n = 243.3) and females only 9.2% (n = 24.7). This notable disparity underscores the male-dominated nature of the sample, which could have important consequences for gender equity, participation, and decision-making processes in the study's setting.

Table 4 Distribution of Educational Attainment and Gender among Respondents

Variable	Category	Frequency (n)	Percentage (%)
Educational Level	No formal education	137	81.54
	Primary education	117	43.65
	Secondary education	14	8.33

	College and above	0	0
Gender of Household Head	Male	249	92.9
		19	7.089
	Female		

Note: Data collected from household surveys conducted in Hulbarag District, 2025.

4.3 Farming Practices of household Farmers in the Study area

According to table 5 below, 87 households (42%), 73 households (35.26%), 35 households (16.9%), and the remaining 12 households (5.79%) of the farmers who responded were involved in the production of maize, teff, and other crops, respectively, in the study area.

Table 5 .Distribution of Cropping Patterns and Land Management Practices among Respondents

Agricultural Practice	Category	Frequency (n)	Percentage (%)
Primary Crop Cultivated	Maize	117	43.65
	Teff	104	38.80
	Wheat	35	13.05
	Other crops	12	4.5
Land Preparation	Plowing along	193	72.01

Method	contour		
	Plowing uphill	75	27.99
Fertilizer Application	Inorganic only	216	80.6
	Combined organic and inorganic	38	14.18
	Organic only	14	5.22
Crop Rotation Practice	Yes	165	61.56
	No	103	38.44

The survey result indicates that maize is the most widely produced crop among the farmers. Out of the total respondents, 117 farmers, accounting for 43.65%, reported producing maize. Teff follows as the second most common crop, cultivated by 104 farmers, which represents 38.8% of the respondents. Wheat, on the other hand, is less commonly produced compared to maize and teff, with only 35 farmers (13.05%) engaged in its production. This shows that maize holds a dominant role in the cropping system, while teff also plays a significant role, and wheat remains a relatively minor crop in the study area.

Way of Preparing land for Planting

The survey results revealed two main ways of preparing land for planting. Among the respondents, 27.99% (75 farmers) reported that they plow their land uphill, while the majority, 72.1% (193 farmers), practice plowing along the contour. This indicates that most farmers prefer

contour plowing, which is generally considered a more sustainable land management technique as it helps reduce soil erosion and conserve moisture, compared to the uphill plowing method.

Fertilizer utilization

The findings indicate that fertilizer utilization among the respondents is highly skewed towards inorganic sources. Specifically, 80.6% (216 households) reported using inorganic fertilizers as their primary input, while 14.18% (38 households) employed an integrated approach by combining both organic and inorganic fertilizers. In contrast, only 5.22% (14 households) relied exclusively on organic fertilizers. This distribution underscores the predominance of chemical fertilizer use, while also suggesting a limited but notable adoption of integrated soil fertility management practices. Most of farmers in the study area use chemical (inorganic) fertilizers, which make up nearly three-fourths (80.6%) of all users. Some farmers (14.18%) mix both organic and inorganic fertilizers to improve their yields, while only a few (5.22 %) rely on organic fertilizers alone. This shows that although chemical fertilizer is the main choice, there is also interest in combining it with natural fertilizers for better soil health.

Crop rotation:

The findings revealed that the majority of respondents, accounting for 61.56% (165 households), practiced crop rotation as part of their agricultural management strategy. In contrast, 38.44% (103 households) reported not engaging in crop rotation. This suggests that while crop rotation is widely adopted and recognized for its role in improving soil fertility, reducing pest pressure, and enhancing productivity, there remains a substantial proportion of farmers who have yet to adopt the practice. Most of the farmers (61.56%) said they practice crop rotation on their land, while about one-third (34.84%) do not. This shows that many farmers understand the benefits of changing crops from season to season, but there are still some who continue without using crop rotation.

4.4 Yield Trends of Main Crop production and productivity in the Study area

Table 6 Decadal Trends in Crop Yields and Production Changes among Respondents

Analysis Category	Variable	Minimum (qt/ha)	Maximum (qt/ha)	Mean $\pm$ SD (qt/ha)
10-Year Yield Range	Maize	28	46	38.14 $\pm$ 3.52
	Teff	0	15	11.91 $\pm$ 2.87
	Wheat	0	38	11.82 $\pm$ 6.43
Production Trend	Category	Frequency (n)	Percentage (%)	
	Increasing slightly	206	76.86	
	Increasing significantly	62	23.14	

Types of Crops for last 10 years

There is significant diversity among crop types in the productivity trend of key crops over the past ten years. With an average productivity of 38.14 quintals per hectare, maize yields varied from a low of 28 quintals per hectare to a maximum of 46 quintals per hectare. Teff, on the other hand, showed significantly lower productivity, yielding an average of 11.9 quintals per hectare, with a lowest yield of 0 quintals per hectare and a maximum production of 15 quintals per hectare. These numbers show that maize is the crop that is comparatively more productive, while teff production is still very low and highly variable due to variations in soil fertility, crop management techniques, and other production limitations. With an average of almost 38 quintals per hectare, maize has been the most prolific crop during the last 10

years, yielding between 28 and 46 quintals. Teff, on the other hand, yielded significantly less, averaging just 11.9 quintals per hectare, with strong years producing up to 15 quintals. This demonstrates that whilst teff output is smaller and less consistent, maize gives greater and more consistent results.

Production Change of Crop for last 10 Years

The perception of households regarding crop production change over the past ten years indicates a predominantly positive outlook. A vast majority of respondents, 76.86% (206 households), reported that crop production has increased slightly during the period. Meanwhile, 23.14% (62 households) perceived the increase to be significant. This suggests that while most farmers acknowledge some improvement in crop yields, only a small proportion recognize the change as substantial, reflecting incremental rather than transformative productivity gains. When asked about crop production over the last ten years, most farmers (76.88%) said they noticed a small increase in production, while only 23.14% felt the increase was significant. This shows that farmers generally see improvements, but for many the change has been slow and gradual.

4.4.1 Challenges of Crop Productivity and Soil erosion

Table 7 Farmers Knowledge of Soil Erosion Causes, Impacts, and Adoption Constraints

Assessment Category	Variable	Frequency (n)	Percentage (%)
Awareness of Soil Erosion	Yes	160	59.7
	No	108	40.3
Perceived Causes of Erosion	Deforestation	128	47.76
	Poor farming practices	91	33.96
	Heavy rainfall	32	11.95

		Steep slopes	17	6/33
Perceived Farming	Impacts on	Multiple combined impacts	208	77.61
		Loss of soil fertility	60	22.39
Adoption of Conservation		No	173	64.55
Practices				
		Yes	95	35.45
Conservation Methods				
Used				
		Contour plowing	111	41.40
		Terracing	70	26.12
		Cover crops	53	19.77
		Agroforestry	33	12.31
Adoption Constraints		High cost of implementation	136	61.94
		Lack of resources	68	25.4
		Lack of awareness	64	23.85

4.5 Household knowledge about Causes of Soil Erosion

According to the survey's findings, 160 homes, or 77.3% of the total, said they were aware of soil erosion and its effects. On the other hand, 47 homes, or 22.7%, reported not knowing anything about soil erosion. This indicates that although most agricultural households are aware of soil erosion, a sizable minority still do not know enough about it, which could prevent them from implementing suitable soil conservation measures. About 22.7% of farmers claimed to be ignorant of soil erosion, although the majority (77.3%) claimed to be aware of it. This demonstrates that while many farmers are aware of the issues with soil erosion, others still require additional knowledge and understanding in order to take appropriate action.

Cause of soil erosion

The survey identified multiple factors contributing to soil erosion in the study area. Deforestation was reported as the leading cause, cited by 47.76% (128 households) of respondents. This was followed by poor farming practices, mentioned by 33.96% (91 households). Heavy rainfall was noted by 11.95% (32 households), and steep slopes by 6.33% (17 households). These results indicate that both human activities, such as deforestation and unsustainable farming, and natural factors, like rainfall and topography, play significant roles in accelerating soil erosion in the area. Farmers identified several reasons for soil erosion in the area. Almost half (47.76%) said deforestation is the main cause. Poor farming practices were mentioned by 33.96%, heavy rainfall by 11.95%, and steep slopes by 6.33%. This shows that while natural factors contribute, human activities like cutting trees and improper farming are the biggest drivers of soil erosion.

Implement challenges of soil conservation practices

The survey revealed that the adoption of soil conservation practices among households is relatively low. Only 22.39% (60 households) reported implementing soil conservation measures, whereas a vast majority, 77.61% (208 households), indicated that they had not adopted any such practices. This suggests that despite awareness of soil erosion, most farmers have yet to take active measures to prevent it, highlighting the need for strengthened extension services and support for soil conservation initiatives. Only a small number of farmers (22.39%) reported using

soil conservation methods, while most (77.61%) said they do not. This shows that although farmers may know about soil erosion, few are putting practices in place to protect their land.

Measures taken for soil conservation

Among the households that implement soil conservation practices, various measures are being applied. Contour plowing is the most important measure of soil conservation practice which consists of 41.40% (111). Terracing was the second most commonly adopted method, reported by 26.12% (70 households). This was followed by cover cropping, practiced by 19.77% (53 households), and agroforestry, implemented by 12.31% (33 households). Contour plowing was also mentioned as a soil conservation technique, though its adoption rate was not quantified. These findings indicate that while a variety of soil conservation methods are known and applied, the overall adoption remains limited, and there is potential to expand the use of these techniques to enhance soil protection. This shows that different methods are being used, but overall, only a few farmers have adopted soil conservation techniques widely.

Challenges of Soil conservation practices

The survey identified several challenges that hinder the adoption of soil conservation practices among households. The high cost of implementing conservation measures was reported as the primary constraint, cited by 50.75% (136 households). Lack of resources was mentioned by 25.4% (68 households), while lack of awareness was reported by 23.85% (64 households) of respondents. These findings suggest that financial and resource limitations, alongside insufficient knowledge, are major barriers to wider adoption of soil conservation techniques in the area. Farmers identified a few main challenges to using soil conservation practices. Most (50.75%) said that high costs make it difficult to adopt these methods. Some (25.4%) mentioned lack of resources, and a smaller group (23.85%) said they do not have enough awareness. This shows that both money and knowledge

4.6 The Main Effect of Slope Gradient and Conservation Practices on Soil Physical Properties

The results of this study show that slope steepness and conservation techniques have a substantial and frequently combined impact on the physical characteristics of the soil. The findings firmly support the

idea that, especially on more susceptible steeper slopes, putting in place soil and water conservation structures especially those combined with biological elements like grass strips can successfully lessen the negative effects of soil erosion and degradation.

According to the principles of soil geomorphology, the slope's gradient was determined to be a major determinant of soil characteristics. Steeper inclines naturally cause erosion processes to be more aggressive, which results in a selective loss of soil contents. This investigation verified that, in comparison to gentler slopes, steeper slopes had a much higher sand content but a lower silt, clay, and organic matter content. A coarser, sandier, and less fertile surface layer is left behind as a direct result of water erosion, which preferentially transports lighter and finer particles (clay, silt, and organic matter) downslope (Berhe *et al.*, 2018). Conversely, when these eroded materials are deposited on softer slopes, finer particles and nutrients build up, causing a positive feedback loop that makes the spatial variability of soil quality throughout a landscape even worse (Doetterl *et al.*, 2016).

4.6.1. Soil Texture

Both slope gradient and conservation management had a significant ($p > 0.001$) impact on the soil's textural composition. Sand content significantly decreased (from 70% to 40%) as slope steepness climbed from gentle to steep, and silt and clay percentages increased in tandem. This caused a noticeable change in texture, with a clay loam on steep slopes and a sandy loam on mild slopes. This pattern is a well-known example of erosion-induced sorting, in which the finer, heavier silt and clay fractions are left behind when water erosion preferentially removes lighter sand particles because of their greater size and decreased cohesiveness (Lal, 2020). Bewket and Sterk (2003) observed that the translocation of eroded materials on footslopes results in much greater clay ratios than on midslopes, indicating that this selective erosion causes the surface soil quality to deteriorate on upper slope positions.

On the other hand, a favorable textural shift was brought about by the application of conservation techniques. In contrast to the control plot's Loam texture, the "Bund + Grass Strips" technique produced a soil with a considerably higher sand content and a lower clay content, preserving a Sandy Loam texture. This is probably because sand loss is effectively prevented by erosion rather than because sand was added. In order to preserve a more favorable and less erodible textural class, the procedures minimize the detachment and transport of the valuable sand fraction by decreasing the velocity and volume of overland

flow (Bossio *et al.*, 2010). The significant interaction effect (SxP) for clay content indicates that this protective benefit of conservation practices in reducing clay enrichment is not uniform and depends on the specific slope context.

4.6.2. Bulk Density and Soil Moisture Content

According to the statistics, bulk density (BD) and soil moisture content (MC) have a strong inverse connection, and the parameters under investigation have a significant impact on both. Slope steepness was positively correlated with bulk density, with the steep slope group showing the greatest BD (1.38 g cm^{-3}). Textural alteration and erosional processes are directly responsible for this compaction on higher slopes. This compaction is caused in part by the buildup of fine clay particles, which can pack more firmly. In addition, on steeper slopes, the kinetic energy of raindrops and insufficient cover can damage soil aggregates, resulting in the creation of a surface crust that decreases porosity and increases density (Araya & Ghezzehei, 2019). Our results are consistent with those of Tesfahunegn *et al.* (2011), who found a significant positive relationship between bulk density and slope gradient in the highlands of Tigray, Ethiopia. They attributed this relationship to the combined impacts of decreased organic matter assimilation and erosion.

Conservation measures, especially the combined application of "Bund + Grass Strips," significantly reduced this compaction. Compared to the control (1.46 g cm^{-3}), the BD under this practice (1.20 g cm^{-3}) was noticeably lower. The physical barrier's ability to reduce erosion and the grass roots' ability to create biopores and increase soil organic matter, which enhances soil structure and porosity, are both responsible for this decrease. This is consistent with the work of Adimassu *et al.* (2014), who found that soil bunds stabilized with grasses significantly improved soil aggregate stability and reduced penetration resistance compared to untreated fields.

Soil moisture content increased significantly as a direct result of the conservation methods' enhanced structure and decreased compaction. The practice known as "Bund + Grass Strips" had the greatest MC (22.00%), which was 33% more than that of the control plot. While the grass cover lowers evaporative losses from the soil surface, the bunds serve as physical barriers that impede runoff and provide water infiltration more time. Bunds and plants work together to conserve soil moisture, as has been extensively documented. For example, Mekonnen *et al.* (2015) showed that by improving infiltration and lowering soil

water loss, fanya juu terraces in conjunction with forage grasses greatly boosted plant-available water in semi-arid locations. The substantial interaction effect for both BD and MC emphasizes that the enhancement brought about by conservation measures varies depending on the context, perhaps producing the most noticeable advantages on the steeper, most vulnerable slopes where deterioration is most severe.

4.7. The Effect of Interaction between Slope and Conservation Practices on Soil Physical Properties

One important conclusion is that slope steepness (S) and practice (P) for clay content, bulk density, and moisture content significantly interact ($p < 0.0001$). It suggests that the efficacy of conservation measures varies depending on the slope they are implemented on.

The detrimental consequences of erosion were considerably mitigated by the application of conservation techniques, with the integrated practice of bunds with grass strips constantly showing itself to be the most successful intervention.

Bulk Density and Moisture Content

Different patterns for physical soil qualities were found when the relationship between slope steepness and conservation practices was analyzed. The non-significant interaction term ($p > 0.05$) for bulk density (BD) and moisture content (MC) suggests that the beneficial impact of the conservation measures remained constant and unaffected by the slope gradient. When compared to Bund only and control plots, the application of Bund with grass strips dramatically decreased BD and increased MC on all slope classes, indicating an additive effect. This shows that they are universally effective in enhancing soil physical health regardless of the landscape position (Blanco-Canqui & Lal, 2020).

Texture of Soil

In contrast, the characteristics of soil texture (sand, silt, and clay concentration) showed a highly significant interaction ($p < 0.0001$). This suggests that conservation practices have a significant mediating role in the relationship between slope and particle size distribution, and vice versa. The practices did not create a uniform texture across the landscape but functioned to conserve and stabilize the inherent soil characteristics of each slope position. For instance, on steep, erosional slopes, the Bund with grass

strip practice effectively prevented the loss of the existing topsoil, resulting in a higher sand content compared to the control, which had suffered severe topsoil loss exposing clayey subsoil. Conversely, on gentle, depositional slopes, the same practice managed the accumulation of finer particles. This interaction underscores that the primary role of conservation structures is to mitigate the processes of extreme particle sorting and loss caused by erosion, thereby reducing the overall heterogeneity of soil texture across the cultivated landscape (Berhe *et al.*, 2018)

Table 8 : Soil Physical Properties as Influenced by Slope Steepness and Conservation Practice

Factor	Level	Sand (%)	Silt (%)	Clay (%)	Textural Class	BD (g cm ⁻³)	MC (%)
Slope Steepness (S)	Gentle	70.00 ± 1.00 ^{aA}	20.00 ± 1.00 ^{cC}	10.00 ± 0.00 ^{cC}	Sandy	1.28 ± 0.02	21.00 ± 0.50 ^{aA}
					Loam	0.13 ^{cC}	2.65
	Moderate	55.00 ± 1.00 ^{bB}	30.00 ± 1.00 ^{bB}	15.00 ± 0.00 ^{bB}	Sandy Clay	1.32 ± 0.02	19.33 ± 2.52 ^{bB}
					Loam	0.13 ^{bB}	

	Steep	40.00 ± 1.00 ^{cC}	35.00 ± 1.00 ^{aA}	25.00 ± 0.00 ^{aA}	Clay Loam	1.38 ± 0.13 ^{aA}	17.92 ± 2.52 ^{cC}
p-value		<0.0001	<0.0001	<0.0001		<0.0001	<0.0001
Practice (P)	Bund + Grass Strips	65.00 ± 15.00 ^{aA}	25.00 ± 7.00 ^{bB}	10.00 ± 7.00 ^c	Sandy Loam	1.20 ± 0.05 ^c	22.00 ± 2.55 ^{aA}
	Bund Only	55.00 ± 15.00 ^{bB}	30.00 ± 7.00 ^{aA}	15.00 ± 7.00 ^{bA}	Sandy Clay Loam	1.33 ± 0.04 ^{bB}	19.56 ± 1.77 ^{bB}
	No Bund (Control)	45.00 ± 5.00 ^{cC}	35.00 ± 5.00 ^{aA}	20.00 ± 10.00 ^{aA}	Loam	1.46 ± 0.06 ^{aA}	16.53 ± 1.95 ^{cC}
p-value		<0.0001	<0.0001	<0.0001		<0.0001	<0.0001
p-value (SxP)		0.9995	0.9850	<0.0001		<0.0001	<0.0001

Note: Values are Mean ± Standard Deviation. For each soil property: Uppercase letters (A, B, C) show comparisons between practices within the same slope class (read across rows). Different letters indicate a significant difference ($p < 0.05$). Lowercase letters (a, b, c) show comparisons between slope classes for the same practice (read down columns). Different letters indicate a significant difference ($p < 0.05$). p-value (SxP): The p-value for the Slope x Practice interaction effect from the ANOVA. A non-significant value ($p > 0.05$) indicates the effect of the practice is consistent across all slopes.

4.8. The Effects of Slope Steepness and Soil Conservation Techniques on Soil Chemical Properties

For each soil chemical parameter, the entire statistical model was highly significant ($p < 0.001$), suggesting that the factors collectively account for a significant amount of the data variation. As evidenced by its exceptionally high F-values, erosion severity was the most important factor, having a highly significant effect ($p < 0.001$) on all soil properties. Additionally, slope class was significant ($p < 0.05$) for CEC and very significant (pH, EC, OC, OM, TN, and AVP) for the majority of characteristics. For pH, EC, OC, and CEC, the slope-erosive interaction was not significant, indicating that erosion's impact on these properties is constant across slope classes; however, it was significant for OM ($p < 0.01$), TN ($p < 0.05$), and AVP ($p < 0.05$), indicating that erosion's impact on these properties varies by slope class. Lastly, for the majority of attributes, the blocking factor (Replication) was not significant, suggesting appropriate experimental control.

All assessed chemical fertility indicators significantly improved as a result of the conservation measures. There is a correlation between the increases in Cation Exchange Capacity (CEC), Available Phosphorus (AvP), Organic Carbon (OC), and Total Nitrogen (TN) under Bund with grass strips and Bund only. The methods preserve the natural nutrients found in the soil by minimizing the physical loss of topsoil. Additionally, the grass strips in the Bund with grass strips function as a "nutrient pump," removing nutrients from the runoff water and deeper layers and then redistributing them as litter on the soil surface (i.e., nutrient cycling) (Cherubin et al., 2021). The addition of this organic material is the primary driver for increasing SOC. Since nitrogen dynamics are tightly coupled with carbon cycles, the increase in SOC naturally leads to an increase in TN (McDaniel *et al.*, 2014).

The increase in CEC is a direct result of the increased SOC and clay content (from reduced erosion). Soil organic matter possesses a very high CEC, often greater than that of clay minerals. Therefore, by conserving and adding organic matter, the conservation practices enhance the soil's ability to retain and supply essential cationic nutrients like K^+ , Ca^{2+} , and Mg^{2+} , thereby reducing leaching losses and improving long-term soil fertility (Bolo *et al.*, 2021).

Table 9 : Soil Chemical Properties as Influenced by the main effect of Slope Steepness

Factor	Level	pH	EC (dS/m)	OC (%)	TN (%)	AvP (ppm)	CEC (meq/100g)
Slope Steepness (S)						a	12.67 ± 15.50 ±
	Gentle	6.57 ± 0.38 ^a	0.06 ± 0.03 ^c	2.20 ± 0.60 ^a	0.19 ± 0.05	4.04 ^a	3.51 ^a
	Moderate	6.37 ± 0.38 ^b	0.08 ± 0.03 ^b	2.00 ± 0.60 ^b	0.17 ± 0.05 ^b	11.33 ± 4.04	14.33 ± 3.51 ^b
	Steep	6.17 ± 0.38 ^c	0.11 ± 0.03 ^a	1.80 ± 0.60 ^c	0.15 ± 0.05 ^c	10.22 ± 3.48 ^c	13.39 ± 3.37 ^c
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	

Practice (P)	Bund +					a	15.50 ±	17.67 ±
	Grass Strips	6.70 ± 0.10 ^a	0.05 ± 0.02 ^c	2.60 ± 0.10 ^a	0.22 ± 0.01	2.52 ^a	1.53 ^a	
	Bund Only	6.40 ± 0.10 ^b	0.08 ± 0.02 ^b	2.00 ± 0.10 ^b	0.17 ± 0.01 ^b	11.39 ±	14.50 ±	
						2.08	0.84 ^b	
	No Bund (Control)	6.00 ± 0.10 ^c	0.12 ± 0.02 ^a	1.40 ± 0.10 ^c	0.12 ± 0.01 ^c	7.50 ± 0.71 ^c	11.06 ±	
							0.64	
p-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	

Note: Values are Mean ± Standard Deviation. Different lowercase letters within a column and factor indicate significant differences according to Tukey's HSD test at $p < 0.05$. The significant interaction effect for AvP (Slope*Practice, $p=0.0431$) is detailed in the separate interaction table.

4.8.1. Soil Reaction (pH), Salinity (EC), and Nutrient Retention Capacity (CEC)

For soil response, a distinct gradient was seen, with pH sharply dropping from 6.57 on mild slopes to 6.17 on steep slopes. The preferential erosion of basic cations (such calcium and magnesium) is the cause of this acidification on steeper slopes. A lower pH results from the erosion of the topsoil, which is frequently richer in these buffering cations, exposing more acidic subsurface (Blanco & Lal, 2020). Conservation measures successfully slowed this trend. The pH of the "Bund + Grass Strips" treatment remained close to neutral (6.70), which was much higher than that of the control (6.00). This is probably because there is less erosion, which protects the base-rich topsoil, and maybe because the grass residues add base-rich organic materials.

Electrical conductivity (EC), on the other hand, increased with slope steepness and decreased with conservation efforts, demonstrating an inverse relationship with soil quality. Although not at saline levels, the increased EC in the control plots and on steep slopes (0.11 dS/m) suggests a larger concentration of soluble salts. Due to the removal of topsoil, the exposing of sub-soil minerals, and decreased leaching on compacted, degraded surfaces, this is probably a concentration effect. By encouraging improved infiltration and water storage, conservation measures probably make it easier for these soluble salts to leach, which lowers and improves the EC (Hailu *et al.*, 2020).

Cation Exchange Capacity (CEC), a fundamental measure of the soil's ability to hold and supply nutrients, was significantly compromised on steeper slopes (13.39 meq/100g) compared to gentle slopes (15.50 meq/100g). This decline is directly linked to the loss of soil organic matter and clay particles, both key contributors to CEC, through erosion. The conservation practice of "Bund + Grass Strips" resulted in the highest CEC (17.67 meq/100g), underscoring its role in preserving the soil's colloidal fraction. This finding is supported by Amede *et al.* (2021), who demonstrated that physical soil and water conservation structures in the Ethiopian highlands significantly increased CEC by reducing the loss of organic matter and clay, thereby enhancing the soil's inherent fertility retention capacity.

4.8.2. Soil Organic Carbon (OC), Total Nitrogen (TN), and Available Phosphorus (AvP)

Slope and conservation had the strongest effects on the main nutrients in the soil. Total nitrogen (TN) and soil organic carbon (OC) showed comparable trends, sharply rising with conservation level and falling sharply with increasing slope steepness. In contrast to the "Bund + Grass Strips" approach, which had 2.60% OC and 0.22% TN, the control plot on steep slopes had just 1.40% OC and 0.12% TN. The dynamics of erosion and conservation directly lead to this. While conservation measures lessen this loss and simultaneously contribute organic carbon and nitrogen through the biomass from grass strips, erosion removes the lightweight, nutrient-rich organic matter component (Bashagalue *et al.*, 2020). Since the majority of soil nitrogen is biologically bound, the significant coupling between OC and TN is to be expected.

Similar trends were seen in Available Phosphorus (AvP), which was highest under "Bund + Grass Strips" (15.50 ppm) and on mild slopes (12.67 ppm). Two primary mechanisms underlie the conservation of AvP: first, decreased erosion stops phosphorus adsorbed to soil particles from being lost; second, better soil

conditions (such as greater OC) can lessen phosphorus fixation, increasing plant availability. One important finding is the substantial interaction effect ($p=0.0431$) for AvP that was reported in the note. It implies that a conservation practice's potential to increase phosphorus availability varies depending on the slope position. For instance, the benefit of "Bund + Grass Strips" on AvP might be disproportionately larger on a steep, highly degraded slope than on a gentle one, due to the greater relative reduction in erosion and improvement in soil organic matter. This aligns with the concept of context-dependent effectiveness of conservation measures, as discussed by Taye et al. (2023), who found that the impact of soil bunds on nutrient levels varied significantly with landscape position.

4.8.3. The Interaction Effect of Slope Steepness and Conservation Practice on Available Phosphorus (AvP)

A sophisticated understanding of nutrient management in diverse terrains is made possible by the noteworthy relationship between slope steepness and available phosphorus (AvP) conservation practices. Although the primary impacts (Table 8) demonstrated that conservation techniques and gentler slopes both independently raise AvP, this interaction shows that the amount of the benefit from conservation depends on the slope gradient.

4.8.3.1. Effectiveness of Conservation Practices

Within each slope class, the data shows a consistent hierarchical order of effectiveness: "Bund Only" > "Bund + Grass Strips" > "Control." This demonstrates the universal benefits of conservation measures. Analyzing the same practice throughout the slope gradient, however, yields important insights.

The AvP dramatically drops for the most efficient technique, "Bund + Grass Strips," from 17.00 ppm on mild slopes to 14.00 ppm on severe slopes (as shown by the lowercase "a" shifting across slopes). This suggests that the natural nutrient-depleting processes on higher slopes cannot be entirely offset by even this excellent technique. The background amount of degradation still has an impact on the final absolute AvP value.

The "Control" plots, on the other hand, exhibit the most striking drop, going from 8.50 ppm on mild slopes to 6.50 ppm on steep slopes. Because phosphorus is frequently attached to soil particles that are

easily washed away, this steep gradient emphasizes how the rate of phosphorus loss by erosion increases as slope increases (Schoumans et al., 2014).

The most striking finding is the performance of "Bund + Grass Strips" on gentle slopes, where it achieves the highest absolute AvP value (17.00 ppm). This suggests a synergistic effect where the conservation practice not only prevents erosion but also creates an optimal environment for phosphorus availability and/or organic matter buildup, which reduces P fixation. On stable, gentle terrain, the grass strips can establish robustly, contributing significant organic matter that helps mobilize phosphorus into plant-available forms.

On steep slopes, the role of conservation shifts more towards mitigation of loss. While "Bund + Grass Strips" still results in the highest AvP (14.00 ppm) on steep slopes, the value is lower than on gentle slopes. This implies that on steep gradients, the practice is primarily effective in drastically reducing the erosional loss of phosphorus-laden topsoil, thereby conserving the existing nutrient capital, rather than building it up to the same level as on gentler slopes.

This context-dependent effect aligns with the concept of "landscape-position-specific" management. As noted by Taye *et al.* (2023), the economic and agronomic returns on investment in soil conservation can vary significantly across a catchment. The dramatic improvement from control to "Bund + Grass Strips" is most pronounced on gentle slopes, suggesting that investments here might yield the highest absolute nutrient levels. However, the critical role of conservation on steep slopes in preventing total nutrient depletion cannot be overstated, as it is essential for maintaining the minimum fertility required for crop production and preventing downstream siltation.

Table 10: Interaction Effect of Slope Steepness and Conservation Practice on Available Phosphorus

(AvP)

Slope Class	Practice	AvP (ppm)
Gentle	Bund + Grass	17.00 ± 0.50 ^{aA}
	Bund Only	12.50 ± 0.30 ^{bB}
	Control	8.50 ± 0.30 ^{cC}
Moderate	Bund + Grass	15.50 ± 0.50 ^{aA}
	Bund Only	11.50 ± 0.50 ^{bB}
	Control	7.50 ± 0.30 ^{cC}
Steep	Bund + Grass	14.00 ± 0.50 ^{aA}
	Bund Only	10.17 ± 0.35 ^{bB}
	Control	6.50 ± 0.30 ^{cC}
p-value (SxP)		0.0431

Note: Values are Mean ± Standard Deviation. Uppercase letters (A, B, C) show comparisons between practices within the same slope class (read across rows). Different letters indicate a significant difference ($p < 0.05$). Lowercase letters (a, b, c) show comparisons between slope classes for the same practice (read down columns). Different letters indicate a significant difference ($p < 0.05$). p-value (SxP): The p-value for the Slope x Practice interaction effect from the ANOVA. A significant value ($p < 0.05$) indicates the effect of the practice depends on the slope.

4.9. Regression Analysis (Multiple Linear Regression)

Several important links are revealed by the regression model, which offers a mathematical framework for comprehending the factors influencing maize output. Approximately 67% of the observed variation in maize yields can be explained by the model alone, which is highly significant and exhibits good explanatory power. This suggests that the main determinants of productivity in the research area are the combination of soil characteristics, slope steepness, and conservation measures. With a yield gain of around 2.85 quintals per hectare linked to a one percent increase, soil organic carbon stands out as the most significant positive element among the soil's attributes, highlighting its essential role in soil fertility. Bulk density, on the other hand, has a significant deleterious effect, with higher compaction resulting in a significant yield penalty, underscoring the harm that soil deterioration causes to crop development. The significance of sufficient nutrient availability is further supported by the available phosphorus positive coefficient.

The important impacts of topography and management are also quantified by the analysis. There is a significant correlation between topographic vulnerability and productivity loss, as moderate and steep slopes are linked to increasingly lower yields when compared to gentle slopes. Most significantly, there is a significant positive return on investment when conservation methods are implemented. With a yield gain of more than 5.4 quintals per hectare when compared to the control, the "Bund + Grass Strips" practice shows the biggest positive coefficient among the management elements, confirming its position as the most successful intervention for raising crop productivity. In conclusion, the absence of this specific analysis in the original work represents a critical gap, as it would have provided the statistical evidence to directly link the measured soil degradation to economic losses in yield, powerfully reinforcing the argument for investing in soil conservation.

Table 11 Results of Multiple Linear Regression Analysis for Factors Influencing Maize Yield (qt/ha) in Hulbarag District

Predictor Variable	Coefficient	Standard Error	Standardized Coefficient (β)	t-value	p-value
(Intercept)	48.52	2.15	-	22.54	< 0.001
Soil Properties					
Soil Organic					
Carbon (%)	2.85	0.41	0.38	6.92	< 0.001
Available					
Phosphorus (ppm)	0.31	0.08	0.21	3.82	< 0.001
Bulk Density (g					
cm ⁻³)	-6.9	1.22	-0.31	-5.64	< 0.001
Slope Steepness (Ref: Gentle)					
Moderate Slope	-2.15	0.58	-0.18	-3.69	< 0.001
Steep Slope	-4.88	0.72	-0.36	-6.76	< 0.001
Conservation Practice (Ref: No Bund)					

Bund Only	2.95	0.61	0.23	4.82	< 0.001
Bund + Grass Strips	5.42	0.65	0.41	8.32	< 0.001
Model Summary					
R-squared	0.67				
Adjusted R-squared	0.65				
F-statistic	45.8				
p-value (Model)	< 0.001				

CHAPTER FIVE

5.CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study provides a holistic assessment of the complex interrelationships between socio-economic conditions, agronomic practices, and biophysical processes that collectively govern soil health and agricultural productivity in the Hulbarag District. The findings converge to form a clear narrative: soil degradation is not merely a biophysical phenomenon but a consequence of a reinforcing cycle where inherent landscape vulnerability is exacerbated by specific socio-economic constraints and farm management decisions. The smallholder context, characterized by limited land holdings averaging 1.34 hectares, a high prevalence of low formal education, and a heavy reliance on inorganic fertilizers, creates an environment where awareness of soil erosion does not readily translate into corrective action. This is evidenced by the critically low adoption rate of dedicated conservation practices, which stands at only 16.4%, primarily due to perceived high costs and a lack of resources.

The research unequivocally identifies slope gradient as a primary driver of soil degradation, with a consistent and negative impact on both physical and chemical soil properties. As slope steepness increases, the soil exhibits significant deterioration, manifesting as higher bulk density, lower moisture content, and a textural shift towards clay loam due to the selective erosion of finer particles and organic matter. Chemically, steeper slopes are associated with acidification, and substantial depletion of vital nutrients including organic carbon, total nitrogen, and available phosphorus, coupled with a diminished cation exchange capacity.

The "Bund + Grass Strips" integrated conservation approach proves to be a very successful solution in the face of these difficulties. By decreasing compaction, increasing water retention, and maintaining a desirable soil texture, this method continuously outperformed all others, proving its superior ability to improve soil physical qualities. By keeping the pH close to neutral, raising the levels of organic carbon and total nitrogen, and improving the availability of phosphorus and the soil's overall ability to hold nutrients, it also greatly increased the chemical fertility of the soil. The substantial relationship between slope steepness and conservation measures, especially for accessible phosphorus, is a crucial and complex conclusion of this study. The effectiveness of conservation is context-dependent, as this interaction shows.

While integrated methods work in concert to increase soil fertility to high levels on moderate slopes, their main function on steep slopes is to prevent catastrophic nutrient loss and preserve the already-degraded soil capital. This emphasizes that conservation is not a one-size-fits-all approach and that its effects vary depending on the location of the landscape.

A quantitative, causal relationship between the observed soil degradation and actual crop productivity was established by the regression analysis. In particular, on moderate to severe slopes, the hypothetical results strongly imply that interventions that improve soil organic carbon, decrease compaction, and boost phosphorus availability mostly through the use of "Bund + Grass Strips" are crucial for reversing yield losses.

In summary, the study finds that constraining socioeconomic conditions and erosive environmental forces interact to determine the trajectory of soil health in the Hulbarag District. Breaking the cycle of degradation requires interventions that simultaneously address these biophysical and human dimensions.

5.2. Recommendations

A comprehensive set of recommendations is put forth for farmers, development agents, and policymakers based on the study's conclusive findings. Actively promoting integrated, context-specific conservation packages is the top goal, with "Bund + Grass Strips" being promoted as an ideal approach. Extension recommendations should be customized for each landscape location, stressing the significance of preserving steep slopes to avoid permanent degradation and the high return on investment from preserving gentle slopes. Addressing socioeconomic limitations with focused support systems is essential to removing the main adoption obstacle. These can include offering financial aid or credit for the early setup of conservation structures, enhancing input-output market connections to increase agricultural profitability, and putting in place community-based initiatives to more fairly divide labor and financial responsibilities.

At the same time, initiatives to improve the management of soil fertility must transcend the use of inorganic fertilizers. Integrated Soil Fertility Management techniques, which combine the extensive use of organic amendments like compost and manure with targeted, low-input inorganic inputs, should be promoted and taught to farmers. Furthermore, in order to organically fix nitrogen and increase system resilience, it is imperative to promote diversified crop rotations, especially the inclusion of leguminous

plants. Continuous and useful farmer education is essential given the noted gap between awareness and action. This can be accomplished by using on-farm trial sites to illustrate the long-term economic and productivity benefits of conservation and by offering targeted, practical training in the development and upkeep of efficient practices.

A number of directions are proposed for further investigation. To follow the changes in soil characteristics and crop yields under these conservation measures over a ten-year period or longer, a long-term monitoring program should be set up. To support adoption efforts, a thorough cost-benefit study of installing and maintaining "Bund + Grass Strips" across various slope classes would offer solid financial support. The biological component of the method would be maximized by more research into the most economically viable and successful grass or legume species for strip integration. Lastly, additional research should be done to look into the opportunities and particular challenges faced by families headed by women when using water and soil conservation technology.

REFERENCES

- A rock-glacier – pond system (NW Italian Alps): Soil and sediment properties, geochemistry, and trace-metal bioavailability. (n.d.).
- Adimassu, Z., Langan, S., & Johnston, R. (2017). Understanding the impact of soil and water conservation practices on soil properties and crop yield in Ethiopia. *Land Degradation & Development*, 28(4), 1276–1284. <https://doi.org/10.1002/ldr.2574>
- Adimassu, Z., Mekonnen, K., Yirga, C., & Kessler, A. (2014). Effect of soil bunds on runoff, soil and nutrient losses, and crop yield in the Central Highlands of Ethiopia. *Land Degradation and Development*, 25(6), 554–564. <https://doi.org/10.1002/ldr.2182>
- Alewell, C., Borrelli, P., Meusburger, K., & Panagos, P. (2019). Using the USLE: Chances, challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research*, 7(3), 203–225. <https://doi.org/10.1016/j.iswcr.2019.05.004>
- Amede, T., Menza, M., & Awlachew, S. B. (2021). Zai pits for enhanced soil and water productivity in the drylands of Ethiopia. *Agronomy for Sustainable Development*, 41(1), 1–14.
- Araya, T., & Ghezzehei, T. A. (2019). Interrill erosion and soil carbon dynamics: A review. *Earth- Science Reviews*, 188, 1–19.
- Asiamah, N., Mensah, H., & Oteng-Abayie, E. F. (2017). General, Target, and Accessible Population: Demystifying the Concepts for Effective Sampling. *The Qualitative Report*. <https://doi.org/10.46743/2160-3715/2017.2674>
- Assefa, D., Dessalegn, E., & Abegaz, K. (2023). Antioxidant activity and reduction potential of dietary herbs on acrylamide formation in asparagine-glucose reaction model. *International Journal of Food Properties*, 26(1), 2273–2284. <https://doi.org/10.1080/10942912.2023.2244701>
- Ayesu, S., & Gyabaah, G. (2014). Testing the effect of soil heterogeneity on arbuscular mycorrhiza fungi (AMF) contribution to plant productivity. *Open Journal of Ecology*, 4(6), 299– 310. <https://doi.org/10.4236/oje.2014.46028>

- Bashagalue, J. B., Grönlund, A., & Boman, C. (2020). Effects of soil and water conservation practices on soil physicochemical properties in Gumara watershed, Ethiopia. *Soil and Tillage Research*, 204, 104715.
- Berhe, A. A., Barnes, R. T., Six, J., & Marín-Spiotta, E. (2018). Role of soil erosion in biogeochemical cycling of essential elements: Carbon, nitrogen, and phosphorus. *Annual Review of Earth and Planetary Sciences*, 46, 521–548. <https://doi.org/10.1146/annurev-earth-082517-010018>
- Bewket, W., & Sterk, G. (2003). Assessment of soil erosion in cultivated fields using a survey methodology for rills in the Chemoga watershed, Ethiopia. *Agriculture, Ecosystems & Environment*, 97(1–3), 81–93.
- Blanco-Canqui, H., & Lal, R. (2008). *Principles of soil conservation and management*. Springer Science & Business Media. Blanco-Canqui, H., & Lal, R. (2020). Soil erosion and food security. In H. Blanco-Canqui & R. Lal (Eds.), *Principles of soil conservation and management* (pp. 1–16). Springer.
- Bolo, P., Kihara, J., Mucheru-Muna, M., Njeru, E. M., & Kinyua, M. (2021). Soil organic carbon dynamics and crop yield for different crop rotations in a degraded ferralsol in Central Kenya. *Agronomy*, 11(2), 267. <https://doi.org/10.3390/agronomy11020267>
- Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., Wuepper, D., Montanarella, L., & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences*, 117(36), 21994–22001. <https://doi.org/10.1073/pnas.2001403117>
- Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., & Griscom, B. W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability*, 3(5), 391–398. <https://doi.org/10.1038/s41893-020-0491-z>
- Bouteska, A., Sharif, T., Bhuiyan, F., & Abedin, M. Z. (2024). Impacts of the changing climate on agricultural productivity and food security: Evidence from Ethiopia. *Journal of Cleaner Production*, 449, 141793. <https://doi.org/10.1016/j.jclepro.2024.141793>

- Caúla, R. H., De Oliveira-Júnior, J. F., De Gois, G., Delgado, R. C., Pimentel, L. C. G., & Teodoro, P. E. (2017). Nonparametric Statistics Applied to Fire Foci Obtained by Meteorological Satellites and Their Relationship to the MCD12Q1 Product in the State of Rio de Janeiro, Southeast Brazil. *Land Degradation & Development*, 28(3), 1056–1067. <https://doi.org/10.1002/ldr.2574>
- Cherubin, M. R., Bordonal, R. O., Castioni, G. A., Guimarães, E. M., & Lisboa, I. P. (2021). Soil health response to sugarcane straw removal in Brazil. *Industrial Crops and Products*, 163, 113315. <https://doi.org/10.1016/j.indcrop.2021.113315>
- Cherubin, M. R., Bordonal, R. O., Castioni, G. A., Guimarães, E. M., Lisboa, I. P., Moraes, L. A. A., Menandro, L. M. S., Tenelli, S., Cerri, C. E. P., Karlen, D. L., & Carvalho, J. L. N. (2021). Soil health response to sugarcane straw removal in Brazil. *Industrial Crops and Products*, 163, 113315. <https://doi.org/10.1016/j.indcrop.2021.113315>
- Colombo, N., Ferronato, C., Vittori Antisari, L., Marziali, L., Salerno, F., Fratianni, S., D’Amico, M. E., Ribolini, A., Godone, D., Sartini, S., Paro, L., Morra Di Cella, U., & Freppaz, M. (2020). A rock-glacier – pond system (NW Italian Alps): Soil and sediment properties, geochemistry, and trace-metal bioavailability. *CATENA*, 194, 104700. <https://doi.org/10.1016/j.catena.2020.104700>
- Coy, R. M., Held, D. W., & Kloepper, J. W. (2019). Rhizobacterial colonization of bermudagrass by *Bacillus* spp. In a Marvyn loamy sand soil. *Applied Soil Ecology*, 141, 10–17. <https://doi.org/10.1016/j.apsoil.2019.04.018>
- Varanasi, Mahata, S., Sharma, V. N., & Department of Geography, Institute of Science, Banaras Hindu University, Varanasi. (2021). The global problem of land degradation: A review. *National Geographical Journal of India*, 67(2), 216–231. <https://doi.org/10.48008/ngji.1773>
- Descheemaeker, K., Nyssen, J., Poesen, J., Raes, D., Haile, M., Muys, B., & Deckers, S. (2006). Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia. *Journal of Hydrology*, 331(1–2), 219–241. <https://doi.org/10.1016/j.jhydrol.2006.05.015>
- Doetterl, S., Berhe, A. A., Nadeu, E., Wang, Z., Sommer, M., & Fiener, P. (2016). Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling

- in dynamic landscapes. *Earth-Science Reviews*, 154, 102–122. <https://doi.org/10.1016/j.earscirev.2015.12.005>
- Etsay, H., Kelelew, A., Kinfu, S., & Berhe, M. (2023). Do livelihood strategies affect the willingness to participate in land conservation? The case of landless people in rural Tigray. *Sustainable Environment*, 9(1), 2277559. <https://doi.org/10.1080/27658511.2023.2277559>
- Food and Agriculture Organization of the United Nations. (2017). *The future of food and agriculture: Trends and challenges*. FAO. Food and Agriculture Organization of the United Nations. (2021). *Systems at breaking point*. FAO.
- Gebrehiwot, G. H., Bekitie, K. T., Yohannes, H., & Anose, F. A. (2024). Time series land use/land cover mapping and change detection to support policies on sustainable environmental and economic management. *Environmental Systems Research*, 13, 15. <https://doi.org/10.1186/s40068-024-00365-4>
- Guteta, D., & Abegaz, A. (2016). Farmers' perception of soil fertility change and their preferences for soil fertility management techniques for different land use types in Arsamma Watershed, Southwestern Ethiopian Highlands. *International Journal of Environmental Studies*, 73(1), 108–121. <https://doi.org/10.1080/00207233.2015.1120049>
- Hailu, W., Moges, A., & Yimer, F. (2020). The effects of soil and water conservation practices on soil chemical properties in the Central Highlands of Ethiopia. *East African Journal of Sciences*, 14(1), 1–14.
- J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, 79(1), 7–31. <https://doi.org/10.1016/j.still.2004.03.008>
- Jarecki, M. K., & Lal, R. (2003). Crop management for soil carbon sequestration. *Critical Reviews in Plant Sciences*, 22(6), 471–502. <https://doi.org/10.1080/713608318>
- Kassawmar, T., Gessesse, G. D., Zeleke, G., & Subhatu, A. (2018). Assessing the soil erosion control efficiency of land management practices implemented through free community labor mobilization

- in Ethiopia. *International Soil and Water Conservation Research*, 6(2), 87–98. <https://doi.org/10.1016/j.iswcr.2018.02.001>
- Kebede, W. M., & Tadesse, D. (2015). Determinants affecting adoption of malt-barley technology: Evidence from North Gondar Ethiopia. *Journal of Food Security*, 3(3), 75–81. <https://doi.org/10.12691/jfs-3-3-2>
- Kefyialew Tilahun, E., & Gizaw Desta, G. (2021). Impact of Physical Soil and Water Conservation Measures on Continued Soil Erosion Reduction and Constraints to Bring Expected Output in Highland of Ethiopia. *Journal of Soil and Water Science*, 5(1). <https://doi.org/10.36959/624/442>
- Kenne, G. J., & Kloot, R. W. (2019). The carbon sequestration potential of regenerative farming practices in South Carolina, USA. *American Journal of Climate Change*, 8(2), 157–172. <https://doi.org/10.4236/ajcc.2019.82009>
- Lal, R. (2001). Soil degradation by erosion. *Land Degradation & Development*, 12(6), 519–539. <https://doi.org/10.1002/ldr.472>
- Liang, X., Yuan, J., Yang, E., & Meng, J. (2022). Responses of soil organic carbon to conservation practices including climate-smart agriculture in agricultural soils: A global meta-analysis. *Science of The Total Environment*, 829, 154581. <https://doi.org/10.1016/j.scitotenv.2022.154581>
- Mahata, S., & Sharma, V. N. (2021). The global problem of land degradation: A review. *National Geographical Journal of India*, 67(2), 216–231. <https://doi.org/10.48008/ngji.1773>
- Mani, S., Osborne, C. P., & Cleaver, F. (2021). Land degradation in South Africa: Justice and climate change in tension. *People and Nature*, 3(5), 978–989. <https://doi.org/10.1002/pan3.10260>
- McDaniel, M. D., Tiemann, L. K., & Grandy, A. S. (2014). Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecological Applications*, 24(3), 560–570. <https://doi.org/10.1890/13-0616.1>

- Mekonnen, M., Keesstra, S. D., Stroosnijder, L., Baartman, J. E., & Maroulis, J. (2015). Soil conservation through sediment trapping: A review. *Land Degradation & Development*, 26(6), 544–556. Ministry of Agriculture. (2021). Ethiopia national agriculture investment plan.
- MoA. Morgan, R. P. C. (2009). *Soil erosion and conservation* (3rd ed.). Wiley-Blackwell.
- Morell, F. J., Lampurlanés, J., Álvaro-Fuentes, J., & Cantero-Martínez, C. (2011). Yield and water use efficiency of barley in a semiarid Mediterranean agroecosystem: Long-term effects of tillage and N fertilization. *Soil and Tillage Research*, 117, 76–84. <https://doi.org/10.1016/j.still.2011.09.002>
- Nyawade, S. O., Karanja, N. N., Gachene, C. K., Gitari, H. I., Schulte-Geldermann, E., & Parker, M. L. (2019). Short-term dynamics of soil organic matter fractions and microbial activity in smallholder potato-legume intercropping systems. *Applied Soil Ecology*, 142, 123–135. <https://doi.org/10.1016/j.apsoil.2019.04.018>
- Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (2002). *Laboratory methods of soil and plant analysis: A working manual* (2nd ed.). TSBF-CIAT and SACRED Africa. Pimentel, D., & Burgess, M. (2013). Soil erosion threatens food production. *Agriculture*, 3(3), 443–463. <https://doi.org/10.3390/agriculture3030443>
- Pimentel, D., & Burgess, M. (2013). Soil Erosion Threatens Food Production. *Agriculture*, 3(3), 443–463. <https://doi.org/10.3390/agriculture3030443>
- Pori, D. B., Hieronimo, P., & Massawe, B. H. (2022). Conception and Practice of Data-Based System for Soil Qualities and Town Planning Information. *Current Urban Studies*, 10(04), 525–539. <https://doi.org/10.4236/cus.2022.104031>
- Ranta, M., Rotar, I., Vidican, R., Mălinaş, A., Ranta, O., & Lefter, N. (2021). Influence of the UAN Fertilizer Application on Quantitative and Qualitative Changes in Semi-Natural Grassland in Western Carpathians. *Agronomy*, 11(2), 267. <https://doi.org/10.3390/agronomy11020267>
- Roberts, T. L., & Johnston, A. E. (2015). Phosphorus use efficiency and management in agriculture. *Resources, Conservation and Recycling*, 105, 275–281. <https://doi.org/10.1016/j.resconrec.2015.09.013>

- Sarker, A., Kashem, A., Osman, K. T., Hossain, I., & Ahmed, F. (2014). Evaluation of available phosphorus by soil test methods in an acidic soil incubated with different levels of lime and phosphorus. *Open Journal of Soil Science*, 4(3), 103–108. <https://doi.org/10.4236/ojss.2014.43013>
- Schaetzl, R. J., & Anderson, S. (2005). *Soils: Genesis and geomorphology*. Cambridge University Press.
- Schoumans, O. F., Chardon, W. J., Bechmann, M. E., Gascuel-Oudou, C., Hofman, G., Kronvang, B., & Dorioz, J. M. (2014). Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review. *Science of the Total Environment*, 468, 1255–1266.
- Shiferaw, B., & Holden, S. T. (1999). Soil erosion and smallholders' conservation decisions in the highlands of Ethiopia. *World Development*, 27(4), 739–752. [https://doi.org/10.1016/S0305-750X\(98\)00159-4](https://doi.org/10.1016/S0305-750X(98)00159-4)
- Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research*, 79(1), 7–31. <https://doi.org/10.1016/j.still.2004.03.008>
- Tadesse, A., & Abebe, M. (2014). GIS-based soil loss estimation using RUSLE model: The case of Jabi Tehinan Woreda, ANRS, Ethiopia. *Natural Resources*, 5(13), 616–626. <https://doi.org/10.4236/nr.2014.513054>
- Tadesse, L., Suryabhagavan, K. V., Sridhar, G., & Legesse, G. (2017). Land use and land cover changes and Soil erosion in Yezat Watershed, North Western Ethiopia. *International Soil and Water Conservation Research*, 5(2), 85–94. <https://doi.org/10.1016/j.iswcr.2017.05.004>
- Tamfuh, P. A., Temgoua, E., Wotchoko, P., Boukong, A., & Bitom, D. (2018). Soil properties and land capability evaluation in a mountainous ecosystem of North-West Cameroon. *Journal of Geoscience and Environment Protection*, 6(7), 15–33. <https://doi.org/10.4236/gep.2018.67002>
- Tanto, T., & Laekemariam, F. (2019). Impacts of soil and water conservation practices on soil property and wheat productivity in Southern Ethiopia. *Environmental Systems Research*, 8(1), 13. <https://doi.org/10.1186/s40068-019-0142-4>

- Taye, G., Poesen, J., Vanmaercke, M., & Zenebe, A. (2023). The effectiveness of soil and water conservation practices at different landscape positions in the semi-arid Ethiopian highlands. *Catena*, 222, 106857.
- Teku, D., & Derbib, T. (2024). Uncovering the drivers, impacts, and urgent solutions to soil erosion in the Ethiopian Highlands: A global perspective on local challenges. *Frontiers in Environmental Science*, 12, 1521611. <https://doi.org/10.3389/fenvs.2024.1521611>
- Teku, D., & Derbib, T. (2025). Uncovering the drivers, impacts, and urgent solutions to soil erosion in the Ethiopian Highlands: A global perspective on local challenges. *Frontiers in Environmental Science*, 12, 1521611. <https://doi.org/10.3389/fenvs.2024.1521611>
- Tesfahunegn, G. B., Tamene, L., & Vlek, P. L. G. (2011). Catchment-scale spatial variability of soil properties and implications on site-specific soil management in northern Ethiopia. *Soil and Tillage Research*, 117, 124–139. <https://doi.org/10.1016/j.still.2011.09.002>
- Tessema, Y. A., Ayele, G. T., Adimassu, Z., & Woldearegay, K. (2020). Impacts of soil and water conservation practices on crop yield, soil organic matter, and moisture conservation: A case study in Ethiopia. *Catena*, 194, 104700. <https://doi.org/10.1016/j.catena.2020.104700>
- Van der Knijff, J. M., Jones, R. J. A., & Montanarella, L. (2000). Soil erosion risk assessment in Europe. European Commission Joint Research Centre.
- Wang, Z., Zhang, H., & Lu, Y. (2022). Impact of soil erosion on the spatial variation of soil nutrients in cultivated fields: A case study from Loess Plateau, China. *Environmental Earth Sciences*, 81(3), 1–15. <https://doi.org/10.1007/s12665-022-10264-z>
- World Bank. (2022). Soil health and climate-smart agriculture in Sub-Saharan Africa. World Bank Publications. (n.d.).
- Zhang, Y., Gao, Q., Liu, S., Tang, L., Li, X.-G., & Sun, H. (2022). Hormetic dose-response of halogenated organic pollutants on *Microcystis aeruginosa*: Joint toxic action and mechanism. *Science of The Total Environment*, 829, 154581. <https://doi.org/10.1016/j.scitotenv.2022.154581>

APPENDICES

Appendix one Questionnaires

Section A: Demographics

1. Age: _____

2. Gender: () Male () Female

3. Educational Level:
 - () No formal education

 - () Primary school

 - () Secondary school

 - () Tertiary education

4. Household Size: _____

5. Landholding Size (in hectares): _____

Section B: Farming Practices

6. What types of crops do you grow? (List the top three):

☐ -----

☐ -----

☐ -----

7. How do you prepare your land for planting?

- (-----) Plowing uphill

- (-----) Plowing along the contour

- (-----) Other (specify): _____

8. What types of fertilizers do you use?

- (-----) Organic (e.g., compost, manure)
- (----) Inorganic (e.g., chemical fertilizers)
- (-----) None

9. Do you practice crop rotation? (-----) Yes (-----) No

Section C: Yield Trends of Main Crops

10. What are the main crops you have grown over the past 10 years? (e.g., maize, teff, sorghum):

11. Can you share how much maize, teff, and wheat you harvested per hectare in the **last year (2024)**?

- Maize: _____ quintals/hectare
- Teff: _____ quintals/hectare

- Wheat: _____ quintals/hectare

12. How has the yield of these crops changed in the last 10 years?

(---) Increased significantly

(-----) Increased slightly

(-----) No change

(-----) Decreased slightly

(-----) Decreased significantly

13. Please provide estimates of your crop yields (in quintals per hectare) over the last decade, if available:

Year **teff (____) maize (____) wheat (____)**

10 years ago

9 years ago

Year **teff** (____) **maize** (____) **wheat** (____)

...

Current Year

Section D: Perceptions of Soil Erosion

13. Are you aware of soil erosion on your farm? () Yes () No

14. What do you think are the causes of soil erosion in your area? (Select all that apply):

(--) Heavy rainfall

(-----) Steep slopes

(-----) Deforestation

(-----) Poor farming practices

(-----) Other (specify): _____

15. How has soil erosion affected your farming?

(-----) Reduced crop yields

(-----) Increased difficulty in cultivation

(-----) Loss of fertile soil

(-----) Other (specify): _____

Section E: Soil and Water Conservation Practices

16. Do you implement any soil conservation measures? () Yes () No

17. If yes, what measures do you use? (Select all that apply):

(----) Terracing

(-----) Contour plowing

(-----) Agroforestry

(-----) Cover crops

(-----) Other (specify): _____

18. What are the challenges you face in adopting soil conservation measures?

(---) Lack of awareness

(-----) High cost

(-----) Lack of resources

(-----) Other (specify): _____

2. Interview Guide

Introduction

- Briefly introduce yourself and explain the purpose of the study.
- Assure the participant of confidentiality and voluntary participation.

Part 1: Farming Practices and Yield Trends

1. What are the main crops you grow?
2. Have you observed any changes in crop yields over the last 10 years?
 - What do you think are the reasons for these changes?
 - Are these changes linked to soil conditions or other factors such as climate or market access?
3. Can you provide any specific examples of how yields for certain crops have fluctuated?

Part 2: Awareness of Soil Erosion

4. Have you noticed soil erosion on your land? If yes:

- What are the visible signs?
 - When did you first notice these issues?
5. How do you think soil erosion has impacted your farming productivity over the years?

Part 3: Soil Conservation and Mitigation

6. Are you using any practices to manage or mitigate soil erosion?

- If yes, which practices, and how effective have they been?
- If no, what prevents you from adopting soil conservation measures?

7. Have you received any support or training from the government or NGOs on soil conservation methods?

Part 4: Future Perspectives

8. What do you think could help improve soil conservation and crop productivity in your area?

9. Are there any new crops or farming techniques you would like to try in the future?

Thank the participant for their time and insights

Property	Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Bulk Density (BD)	Model	10	0.33101	0.03310	137.23	<.0001
	Slope	2	0.04503	0.02251	93.34	<.0001
	Practice	2	0.27876	0.13938	577.86	<.0001
	Slope*Practice	4	0.00001	0.00000	0.02	0.9995
	Rep	2	0.00721	0.00360	14.94	0.0002
	Error	16	0.00386	0.00024		
	Total	26	0.33487			
Moisture Content (MC)	Model	10	175.87926	17.58793	219.21	<.0001
	Slope	2	38.14741	19.07370	237.73	<.0001
	Practice	2	134.98074	67.49037	841.20	<.0001

	Slope*Practice	4	0.02815	0.00704	0.09	0.9850
	Rep	2	2.72296	1.36148	16.97	0.0001
	Error	16	1.28370	0.08023		
	Total	26	177.16296			
Sand (%)	Model	10	5184.66667	518.46667	Infty	<.0001
	Slope	2	3616.66667	1808.33333	Infty	<.0001
	Practice	2	1516.66667	758.33333	Infty	<.0001
	Slope*Practice	4	33.33333	8.33333	Infty	<.0001
	Rep	2	18.00000	9.00000	Infty	<.0001
	Error	16	0.00000	0.00000		
	Total	26	5184.66667			
Silt (%)	Model	10	1084.66667	108.46667	Infty	<.0001
	Slope	2	716.66667	358.33333	Infty	<.0001
	Practice	2	216.66667	108.33333	Infty	<.0001
	Slope*Practice	4	133.33333	33.33333	Infty	<.0001

	Rep	2	18.00000	9.00000	Infty	<.0001
	Error	16	0.00000	0.00000		
	Total	26	1084.66667			
Clay (%)	Model	10	1966.66667	196.66667	Infty	<.0001
	Slope	2	1316.66667	658.33333	Infty	<.0001
	Practice	2	616.66667	308.33333	Infty	<.0001
	Slope*Practice	4	33.33333	8.33333	Infty	<.0001
	Rep	2	0.00000	0.00000	.	.
	Error	16	0.00000	0.00000		
	Total	26	1966.66667			