EFFECTS OF DIFFERENT LAND-USE LAND-COVER TYPES AND SLOPE POSITION ON SELECTED PHYSICO-CHEMICAL SOIL PROPERTIES AND SOIL QUALITY IN MAYA-GUDDOO SUBWATERSHED OF MAYA-CITY, EASTERN ETHIOPIA

MSC THESIS

DERIBE DAWIT REGASSA

FEBRUARY 2025
HARAMAYA UNIVERSITY, HARAMAYA

Effects of Different Land-Use Land-Cover Types and Slope Position on Selected Physico-Chemical Soil Properties and Soil Quality in Maya-Guddoo Subwatershed of Maya-City, Eastern Ethiopia

A Thesis Submitted to the School of Natural Resources Management and
Environmental Sciences, Postgraduate Program Directorate
HARAMAYA UNIVERSITY

In Partial Fulfillment of the Requirements for the Degree of
MASTER OF SCIENCE IN AGRICULTURE (SOIL SCIENCE)

Deribe Dawit Regassa

February 2025
Haramaya University, Haramaya

HARAMAYA UNIVERSITY
POSTGRADUATE PROGRAMS DIRECTORATE

As Thesis research advisors, we hereby certify that we have read and evaluated this Thesis entitled **‘‘Effects of Different Land-Use Land-Cover Types and Slope Position on Selected Physico-Chemical Soil Properties and Soil Quality in Maya-Guddoo Subwatershed of Maya-City, Eastern Ethiopia”** prepared under our guidance by Deribe Dawit. We recommend that it be submitted as fulfilling the Thesis requirements.

Samuel Feyissa (PhD)		
Major Advisor	**Signature**	**Date**
Lemma Wogi (PhD)		
Co-Advisor	**Signature**	**Date**

As member of the board of examiners of the MSc Thesis open defense examination, we certify that we have read and evaluated the Thesis prepared by Deribe Dawit and examined the candidate. We recommend that the Thesis be accepted as fulfilling the Thesis requirements for the degree of Master of Science in Agriculture (Soil Science).

Chair Person	Signature	Date
Internal Examiner	Signature	Date
External Examiner	Signature	Date

Final approval and acceptance of the Thesis is contingent upon the submission of the final copy to the Council of Post Graduate Programs (CPGP) through the candidate’s School Graduate Committee (SGC).

DEDICATION

This Thesis is dedicated to my beloved family. Their boundless love, unwavering support and sacrifices have been the cornerstone of this journey.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this Thesis is my own work. I have followed all technical and ethical principles of scholarship in the preparation, data collection, data analysis and compilation of this Thesis. Any scholarly matter that is included in the Thesis has been given recognition through citation.

This Thesis is submitted in partial fulfillment of the requirements for Master of Science in Agriculture (Soil Science) degree at the Haramaya University. The Thesis is deposited in the Haramaya University Library and is made available to borrowers under the rules of the Library. I solemnly declare that this Thesis has not been submitted to any other institution in anywhere for the award of the any academic degree, diploma or certificate.

Brief quotations from this Thesis may be used without specific permission provided that accurate and complete acknowledgement of the source is made. Requests for permission for extended quotations from or reproduction of this Thesis in whole or in part may be granted by the Head of the school when in his or her judgment the proposed use of the material is in the interest of scholarship. In all other instances, however, permission must be obtained from the author of the Thesis.

Name: Deribe Dawit **Signature: __________**

Date: ________________

School: Natural Resources Management and Environmental Sciences (Soil Science)

BIOGRAPHICAL SKETCH

The author, Deribe Dawit Regassa, was born on September 25, 1998 in Yirgalem Town of Sidama Regional State. He completed his primary education at Hunkute Primary School from 2005 to 2012 and his secondary education at Bokesso Secondary School from 2012 to September 2014. He attended his preparatory education at Yirgalem Secondary and Preparatory School from October 2014 to August 2016. After successfully passing the Ethiopian University Entrance Examination (EUEE), he joined Wachemo University in 2017 and graduated with BSc degree in Natural Resource Management in July 2019. After graduating, he was employed at Haramaya University as a Graduate Assistant in October 2020. After two years of service, he joined the Postgraduate Program of Haramaya University in October 2023 to pursue his study leading to Master of Science Degree in Soil Science.

ACKNOWLEDGEMENTS

I want to start by expressing my sincere gratitude to the Almighty God for everything He did, especially for supporting me through every challenge so that I could successfully finish my coursework and Thesis research. Next, I would like to take this opportunity to express my sincere gratitude and appreciation to my major advisor, Dr. Samuel Feyissa, for his unwavering guidance, expertise, support and constructive feedback from the beginning of developing the Thesis research proposal to the completion of the Thesis write-up. Additionally, I am deeply grateful to my co-advisor, Dr. Lemma Wogi, for his insightful advice, steadfast mentorship, guidance and encouragement at every stage of this endeavor.

I would like to thank Haramaya University and the School of Natural Resources Management and Environmental Sciences for admitting me to their Postgraduate Program and fostering a learning atmosphere while I was in campus. I also want to express my gratitude to the Haramaya University soil laboratory staff, especially Mr. Deressa Boja and Mr. Dilnesa Bayle for their genuine approach and their kindness in allowing me to use resources for my research work.

I would like to express my profound appreciation to Mr. Mekonen Keneni for his help during the field observation and the sample collection. Additionally, I want to express my gratitude to the Ganda Maya-Guddoo administration for their unwavering support and direction during field observation and sample collection, as well as to all of the farmers in the Maya-Guddoo subwatershed who allowed me to collect soil samples from their land. Also, I would like to express my heartfelt gratitude to Mr. Jemal Mohammed, the Natural Resource Management Expert at Haramaya sub-city Agriculture Office for his invaluable support and I am also deeply thankful to my colleagues; Dr. Alemu Kebede, Mr. Girma Aseffa, Mr. Misrach Melese and Mr. Lenjisa Tamiru for their unwavering encouragement and guidance throughout this work. Finally, I deeply acknowledge my parents for their care and support throughout my study period.

ACRONYMS AND ABBREVIATIONS

AAS	Atomic Absorption Spectrophotometer
ANOVA	Analysis of Variance
ATA	Ethiopian Agricultural Transformation Agency
AV.P	Available Phosphorus
AWHC	Available Water Holding Capacity
C:N	Carbon to Nitrogen ratio
CEC	Cation Exchange Capacity
DEM	Digital Elevation Model
DTPA	Diethylenetriaminepenta-acetic Acid
EC	Electrical Conductivity
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GPS	Geographic Positioning System
HSD	Honest Significant Difference
ITPS	Intergovernmental Technical Panel on Soils
KSB	Potassium Solubilizing Bacteria
LULC	Land Use Land Cover
MDS	Minimum Data Set
MoANR	Ministry of Agriculture and Natural Resource
MSD	Minimum Significant Difference
NRCS	Natural Resource Conservation Service
OM	Organic Matter
PBS	Percent Base Saturation
PCA	Principal Component Analysis
PWP	Permanent Wilting Point
RDA	Redundancy Analysis
SEP	Socio-economic Profile
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SQI	Soil Quality Index
SSA	Sub-Saharan Africa
STN	Soil Total Nitrogen
TN	Total Nitrogen
TP	Total Porosity
USDA	United States Department of Agriculture

TABLE OF CONTENTS

DEDICATION **iv**
STATEMENT OF THE AUTHOR **v**
BIOGRAPHICAL SKETCH **vi**
ACKNOWLEDGEMENTS **vii**
ACRONYMS AND ABBREVIATIONS **viii**
LIST OF TABLES **xi**
LIST OF TABLES IN THE APPENDIX **xii**
LIST OF FIGURES **xiii**
ABSTRACT **xiv**
1. INTRODUCTION **1**
2. LITERATURE REVIEW **5**
  2.1.The Soil, its Fertility and Quality **5**
  2.2. Physical Indicators of Soil Fertility and Soil Quality **7**
    2.2.1. Soil Texture 7
    2.2.2. Soil Structure 8
    2.2.3. Bulk Density 8
    2.2.4. Soil Water Content 9
  2.3. Chemical Indicators of Soil Fertility and Soil Quality **9**
    2.3.1. Soil Reaction 10
    2.3.2. Electrical Conductivity 10
    2.3.3. Soil Organic Matter 10
    2.3.4. Total Nitrogen 11
    2.3.5. Available Phosphorus 11
    2.3.6. Available Potassium 12
    2.3.7. Cation Exchange Capacity 12
    2.3.8. Extractable Micronutrients 12
  2.4. Biological Indicators of Soil Fertility and Soil Quality **13**
    2.4.1. Earthworms 13
    2.4.2. Soil Enzymes 14
    2.4.3. Particulate organic matter 14
    2.4.4. Microorganisms 14
  2.5. Effects of Land-Use Land-Cover Types on Soil Fertility and Soil Quality **15**
  2.6. Effects of Slope Position on Soil Fertility and Soil Quality **15**
  2.7. Soil Fertility Status in Ethiopia **16**
  2.8. Soil Quality Index **18**
    2.8.1. Minimum Data Set 19
    2.8.2. Computation of Soil Quality Index 19
3. MATERIALS AND METHODS **20**
  3.1. Description of Study Area **20**
    3.1.1. Location 20
    3.1.2. Climate 21
    3.1.3. Geology 21
    3.1.4. Topography and Soils 22
    3.1.5. Farming Systems 22
    3.1.6. Land Use/Land Cover Types 23

TABLE OF CONTENTS (*Continued*)

3.2. Soil Quality Indexing Process 23
3.2.1. Indicator Selection 23
3.2.2. Indicator Interpretation 24
3.2.3. Soil Quality Indexing 25
3.3. Site Selection, Soil Sampling and Sample Preparation 25
3.4. Soil Laboratory Analysis 26
3.5. Data Analysis 27
4. RESULTS AND DISCUSSION 28
4.1. Effects of LULC types and Slope Positions on Physical Properties of Soil 28
4.1.1. Soil Texture 28
4.1.2. Bulk Density and Total Porosity 30
4.1.3. Soil Water Retention Characteristics 31
4.2. Effects of LULC types and Slope Positions on Chemical Properties of Soil 34
4.2.1. Soil Reaction 34
4.2.2. Electrical Conductivity 35
4.2.3. Soil Organic Matter Content 36
4.2.4. Total Nitrogen and Carbon to Nitrogen Ratio 37
4.2.5. Available Phosphorus 38
4.2.6. Cation Exchange Capacity 39
4.2.7. Exchangeable Bases and Percent Base Saturation 40
4.2.8. Extractable Micronutrients 43
4.3. Effects of LULC types and Slope Positions on Soil Quality 45
5. SUMMARY AND CONCLUSIONS 48
6. REFERENCES 50
7. APPENDIX 61

LIST OF TABLES

Table **Page**

1 Description of the dominant land-use land-cover types within Maya-Guddoo subwatershed 23

2 Soil quality indicators and the values of scoring function for evaluating the soil quality indices in the study area. 24

3 The interaction effect of LULC types and slope positions on the physical soil properties in Maya-Guddoo subwatershed 30

4 The interaction effect of LULC types and slope positions on the gravimetric soil water content at FC, PWP, AWHC and MC in the study area 34

5 The interaction effect of LULC types and slope positions on chemical soil properties in Maya-Guddoo subwatershed 40

6 The interaction effect of LULC types and slope positions on basic exchangeable cations and PBS in Maya-Guddoo subwatershed 43

7 Mean values of micronutrients as influenced by LULC types and slope positions 45

8 Interaction effect of LULC types and slope positions on soil quality index in Maya-Guddoo subwatershed and the soil quality classes 46

9 Pearson`s correlation matrix for selected soil properties under different LULC types and slope positions. 47

LIST OF TABLES IN THE APPENDIX

Appendix Table **Page**

1 GPS points of soil sampling sites of different LULC types along slope positions in Maya-Guddoo subwatershed 62
2 The ANOVA summary of physical properties of soil in study area 63
3 Ratings of bulk density and particle size distribution for a given soil 64
4 Rating of soil pH for 1:2.5 soils to water ratio suspension 64
5 Ratings of soil organic matter, total nitrogen, CEC, AV.P and AWHC 64
6 Ratings of Exchangeable Basic Cations 64
7 Ratings of Extractable Micronutrients 65
8 The ANOVA summary of chemical soil properties in Maya-Guddoo subwatershed 65
9 ANOVA summary of Exchangeable Basic Cations and PBS in study area 66
10 ANOVA summary of extractable micronutrients in study area 66
11 ANOVA summary of soil quality index in Maya-Guddoo subwatershed 67
12 The ratings of soil quality index 67

LIST OF FIGURES

Figure **Page**

1 Map of the study area 20

2 Mean monthly rainfall, monthly maximum and minimum temperatures of the study area (1994 - 2023) based on the records from Ethiopian Meteorological Institute 21

Effects of Different Land-Use Land-Cover Types and Slope Position on Selected Physico-Chemical Soil Properties and Soil Quality in Maya-Guddoo Subwatershed of Maya-City, Eastern Ethiopia

ABSTRACT

Soil is a vital resource for agricultural production and environmental sustainability. Soils in SSA suffer from nutrient depletion, leading to low agricultural productivity. The soils in Hararghe are highly degraded due to intensive and continuous cultivation. Gathering fundamental information about soil properties under different LULC types is so vital to guide management techniques and address the problems of declining soil fertility and quality. This study assessed the influence of LULC types and slope position on selected physico-chemical soil properties and soil quality in Maya-Guddoo subwatershed of Maya-City, Eastern Ethiopia. To achieve this, a total of 27 surface composite soil samples (0-20 cm depth) were collected from cultivated, Khat and grazing LULC types across slope positions. For each composite sample, 8-10 sub-samples were randomly collected using the quadrant method. Key soil properties were analyzed by following the standard laboratory procedures. The soil quality was assessed using a SQI from the selected indicators in the MDS. A linear scoring approach was utilized, being categorized as more is better, less is better, or optimal is better for each indicator. Data were analyzed using a two-way factorial ANOVA in R software to assess the main and interaction effects on soil properties. Tukey's HSD test ($p<0.05$) was used to further analyze significant effects in pairwise comparisons. The findings indicate significant differences for most soil parameters. However, the PBS showed non-significant variation. Additionally, silt and AWHC among LULC types and TN across slope positions showed non-significant difference. Grazing LC type on lower slopes, exhibited the highest values of clay content (40.33%), TP (57.09%), FC (38.00%), AWHC (17.54%), OM (4.91%), TN (0.24%), and most exchangeable bases and micronutrients. In contrast, cultivated LU types at upper slope displayed the lowest values of clay content (21.33%), OM (1.95%) and TN (0.09%). Khat LU types presented mixed results, with higher AV.P (23.41mg/kg) and MC (28.57%) at lower and middle slopes but variable values for other indicators depending on slope positions. The soil under Khat and grazing LULC types exhibited comparable SQI values of 0.65 and 0.64, respectively, while the soil under cultivated LU type showed the lowest SQI of 0.62. Among the slope positions, the highest SQI (0.67) was recorded at middle slope followed by the lower slope (0.65), whereas the upper slope had the lowest SQI (0.59). Notably, the middle slope of Khat LU type exhibited the highest soil quality. The study concludes that the LULC types and slope position significantly influence the soil fertility and quality. To lessen soil degradation, especially on upper slopes and intensively farmed areas, sustainable land management techniques like contour-based strip cropping and biochar-compost blends, reduced tillage and organic matter incorporation are recommended. These results offer vital information for improving agricultural productivity in the area and conserving soil. Mandatory residue retention and nitrogen-fixing hedgerows should be implemented in Khat fields to improve soil fertility and quality. In pasturelands, rotational grazing can greatly enhance soil structure and water retention.

Keywords: *Cultivated land, grazing land, Khat cultivation, linear scoring, minimum data set, slope positions, soil quality index*

1. INTRODUCTION

Soil is a mixture of minerals, nutrients, organic matter, water, air and living organisms, as determined by various environmental factors such as climate, parent materials, relief, organisms and time (Anup *et al.*, 2013). Soils in agricultural production are integral part of ecological system which produces our food and fiber (Yared, 2018). All living things directly and indirectly rely on plants and plants grow in soil, making it one of the most important natural resources. Soil as a vital component of the terrestrial ecosystem, is essential for plant growth and supports micro-organisms by fulfilling functions crucial for sustaining life and environmental health (Nwachokor *et al.*, 2009).

Soil fertility is the ability of a soil to sustain plant growth by providing essential plant nutrients and favorable chemical, physical and biological conditions as a habitat for plant growth (FAO, 2023). Additionally, it is a crucial indicator of soil quality for human health, economic development, environmental quality and food production and security (FAO, 2023). Soil fertility depends on various factors such as soil depth, drainage, organic matter, pH and nutrient availability. Soil fertility, which is vital for agricultural productivity and environmental sustainability, can be enhanced through the application of appropriate amendments and the implementation of soil conservation practices. It is governed by the physical, chemical and biological properties of the soil and their interactions (Doran and Zeiss, 2000), which collectively determine soil quality.

Soil quality is the specific capacity of a soil to function within ecosystem boundaries in order to support biological productivity, maintain the quality of air and water, and support human habitation and health (Karlen *et al.*, 1997). According to Carter *et al.* (2002) soil quality is composed of two components: an intrinsic component that covers the soil's inherent ability to support plant growth and a dynamic component that is influenced by the land management or user. Sustainable and productive agriculture is currently very much related with soil quality (Karlen *et al.*, 1997). In this way, soil quality simultaneously addresses sustainability and productivity issues. As a result, soil quality has been discussed worldwide and became a major agenda among the scientific community in recent decades (Karlen *et al.*, 2014b; Sinha *et al.*, 2014).

Soil quality encompasses the physical, chemical and biological properties of the soil. These properties are dependent on soil stocks and nutrient availability and influenced by LULC types as well as a number of other management factors (Tiwar *et al.*, 2006). Land use/land cover types and agricultural management can be considered as the major factors that affect soil quality as a result of the change they bring about to the soil physical, chemical and biological properties (Caravaca *et al.*, 2002).

Soil quality deterioration and fertility decline are becoming the major challenges for establishing sustainable agriculture in Sub-Saharan African countries (Bationo, 2009). This is worsened by the removal of input subsidy, untimely availability and low quality of fertilizers, poor cultural practices, inadequate supplies of organic and inorganic fertilizers, weak agricultural extension services, a lack of soil fertility maintenance plans and nutrient mining and low nutrient use efficiency (Jonas *et al.*, 2012).

Declining of soil quality has posed a threat to agricultural productivity, economic growth and healthy environment on a global scale (Girmay *et al.*, 2008). The underlying causes for declining of soil quality are highly related to improper land use and soil management, erratic and erosive rainfall, steep terrain, deforestation and overgrazing (Girmay *et al.*, 2008). About 65% of the agricultural land in Sub-Saharan Africa is degraded due to poor management practices, which induce declines in soil biological, chemical and physical quality there by reducing the capacity of the soil to support crop production and provide other ecosystem services (Zingore *et al.*, 2015). Annual nutrient depletion were estimated to reach 38 kg/ha (i.e., 26 kg N, 3 kg P, and 9 kg K) in SSA countries (FAO and ITPS, 2015), leaving soils with serious fertility and other constraints (FAO, 2002).

Soils in SSA countries, including Ethiopia are characterized by severe and widespread nutrient depletion, resulting in low agricultural productivity (Chianu and Mairura, 2012). Furthermore, Ermias *et al.* (2016) reported that Ethiopia has extremely high levels of soil degradation due to nutrient extraction which is a sign of the current unsustainable land use and management systems. Declining soil fertility is one of the most significant constraints to increase food production in Ethiopia, which is exacerbated by human activities such as mono-cropping, nutrient mining, improper land use systems and insufficient nutrient replenishment (Gete *et al.*, 2010).

The total hectares of cultivated land in Ethiopia has reached approximately 12 million in mid-2013, but most of the soils are highly degraded (ATA, 2013). As a result, the natural resource has become increasingly depleted with rapid land conversion that leads to unsustainable land management and land degradation (Zeleke, 2010). Such land use conversions have contributed to soil degradation and soil loss by deteriorating the soil physical and chemical properties (Karltun *et al.*, 2013). This alters the value of indicators that have detrimental effect on soil quality. In addition, the heavy reliance on agriculture which is marked by erratic rainfall, inadequate management and steep terrain exacerbates the deterioration of soil quality as a result of soil erosion and nutrient depletion (Yared, 2018).

Soil quality index is a useful assessment tool for managing resources and conserving the soil. Additionally, it can offer the data required for planners and decision makers to decide how best to prevent the deterioration of soil quality by introducing the appropriate interventions (Gebreyesus, 2014). Even though the soil quality index is crucial for preventing the degradation of soil quality, not many studies have been conducted in relation to different LULC types across slope position. This indicated that research on soil quality index has been mostly neglected potentially due to technical and financial limitations (Gebreyesus, 2014).

Although it is impossible to quantify soil quality directly, it can be inferred by measuring the physical, chemical and biological characteristics of the soil, which act as quality indicators (Diack and Stott, 2001). In Ethiopia, very few studies have been done to quantify the appropriate indicators for evaluating and monitoring soil quality, and those that have been done are mostly in the northern parts of the country (Gebreyesus, 2014; Aweke *et al.*, 2015; Yoseph *et al.*, 2017; Yared, 2018). No attempt has been made to generate minimum data set and evaluate soil quality in the eastern part of Ethiopia (Yared, 2018).

The soil resources of Hararghe area are remarkably diverse because of the complex interactions between soil forming factors and processes (Kibebew, 2014). This diversity results in different types of soil that can be found within short distances. However, many soils are either severely degraded or at high risk of degradation as a result of intensive and prolonged cultivation over many years (Kibebew, 2014). In the study area, farmers predominantly cultivate the Khat crop continuously and they seek out new lands for cultivation to satisfy the increasing food demand of the rapidly growing population. According to Wood *et al.* (2024), Khat cultivation has become a primary economic activity in eastern Ethiopia, leading to increased land use and subsequent soil degradation. The shift from food crops to Khat has exacerbated soil erosion and reduced agricultural soil fertility, which is a major concern for food security in the region (Tadesse and Hailu, 2024). Continuous cropping without proper crop rotation and inadequate attention to soil fertility and quality has led to continuous decline in agricultural productivity in the study area. Sustainable soil fertility and quality management techniques are lacking. Therefore, enhancing soil fertility and quality across different LULC types is crucial for improving agricultural productivity and ensuring sustainable soil use in the study area. According to Araba (2021) the adequate knowledge on soil properties at subwatershed level is essential in tackling specific and local problems of agricultural production. High productivity per unit of land can be achieved through improved soil fertility management accompanied by the use of improved crop varieties, pesticides, better agronomic practices and fertilizer application (Manggoel *et al.*, 2014). Additionally, developing management plans for the sustainable use of the soil resource require understanding of soil fertility and quality in relation to different LULC types. This enhances the soil fertility and quality and supports the efforts of farmers to use soils in a sustainable and productive manner.

Therefore, the main objective of this study was to assess the soil fertility status and determine the soil quality under different LULC types in Maya Guddo subwatershed to generate essential baseline information that can aid in identifying suitable management strategies for diverse agricultural activities and guide the implementations of necessary interventions to reverse declining of soil fertility and the degradation of soil quality. Accordingly, the specific objectives of the study were:

- ⇒ To assess the effect of different land-use land-cover types and slope position on selected physico-chemical soil properties and soil quality in the study area.
- ⇒ To determine the soil quality status of the study area based on selected soil quality parameters.

2. LITERATURE REVIEW

2.1. The Soil, its Fertility and Quality

The Natural Resource Conservation Service (NRCS) defines soil as a natural body composed of minerals, organic matter, liquid and gases that occurring on the Earth surface and characterized by horizons or layers, which are distinguishable from the initial material as a result of additions, losses, transfers and transformations of energy and matter or the ability to support rooted plants in a natural environment (Bockheim *et al.*, 2014). According to Arshad *et al.* (2015) the soil is unconsolidated mineral or organic matter on the surface of the Earth that has been subjected to and shows effects of genetic or environmental factors such as climate, macro and micro-organisms and relief acting on parent material over a period of time. It undergoes significant transformations, resulting in distinct physical, chemical, biological and morphological properties that differentiate it from its parent material. Velayutham and Bhattacharya (2000) describe soil as a dynamic natural entity formed as a result of pedogenic processes through the weathering of rocks. Composing both organic and mineral constituents, it possesses physical, chemical, mineralogical and biological properties. Soil varies in depth over the earth's surface and acts as a vital medium for plant growth. A healthy soil supports the growth of a variety of plants, animals and soil microorganisms, efficiently recycles nutrients and retains water and filter pollutants to protect the quality of water, air and other natural resources (Martin *et al.*, 2015).

Soil fertility is the ability of soil to supply nutrients in adequate amounts and in the right proportions to support the growth of particular plants or crops (Martin *et al.*, 2015). It is a part of total soil productivity that deals with the availability of nutrients in the soil and its ability to supply nutrients for crop production both from its own reserves and through external applications (Martin *et al.*, 2015). It integrates biological, chemical and physical properties, all of which affect directly or indirectly nutrient dynamics and availability.

Soil Quality is the ability of a specific type of soil to function in a managed or natural ecosystem to support plants and animals, maintain or improve the quality of the climate, and promote environmental sustainability and human health (Gholamhosseinian *et al.*, 2022). Soil has both inherent and dynamic qualities (USDA, 2006). Inherent soil quality is the natural ability of soil to function; for example, sandy soil drains faster than a clayey one; a deep soil has more room for roots than soils with bedrock near the surface. These characteristics are permanent and do not change easily. The inherent quality of soils is used to evaluate the value or suitability for specific uses, as well as to compare the capabilities of one soil against another. Dynamic soil quality is how soil changes depending on how it is managed (USDA, 2006). Management choices affect the amount of soil organic matter, soil structure, water and nutrient holding capacity. One goal of soil quality research is to learn how to manage soil in a way that improves its functions. This dynamic aspect of soil quality is the focus of assessing and maintaining healthy soil resources (Braimoh and Vlek, 2008).

It is not possible to directly determine the quality of the soil, but it can be inferred by measuring soil physical, chemical and biological properties (Karlen *et al.*, 2004). The process of measuring soil quality necessitates the identification of particular "indicators," called "soil quality indicators," that can be quantitatively measured over time. Soil quality indicators are those soil properties and processes that have the greatest sensitivity to the change in LULC types and management practices in a short-term (Armenise *et al.*, 2013). Soil quality indicators condense a great deal of complexity in the soil and are the quantifiable soil characteristics that influence the capacity of a soil to perform a specified function (Ayoubi *et al.*, 2011).

The indicators of the soil fertility and soil quality are the basic property of the soil that can represent the status of soil fertility and measured to evaluate the quality of the soil in relation to a specific function. These indicators are measurable attributes that reveal the response of the productivity or functionality of the soil to the environment and indicate whether the quality of the soil improves, remains constant or decreases over time (Ghaemi *et al.*, 2014). They give information on the effect of change in the use of the soil and the impact of agricultural practices on its degradation or functioning (Astier *et al.*, 2002). According to Nortcliff (2002), the selection of soil indicator attributes should be based on the LULC types, soil function, reliability of measurement, spatial and temporal variability, sensitivity to changes in soil management, comparability in monitoring systems and skills required for the use and interpretation. Soil attributes that can be used as indicators of soil quality are categorized into physical, chemical and biological types, reflecting different aspects of soil health (USDA, 2006). Physical indicators include soil texture, stoniness, soil structure, bulk density, total porosity, aggregate strength and stability, soil crusting, soil compaction, drainage, water retention, water content, infiltration, hydraulic conductivity and top soil depth. Chemical indicators are soil pH, EC, carbonate content, CEC, Plant nutrients, Sodium saturation and toxic elements. Biological indicators includes organic matter content, populations of organisms, fractions of organic matter, microbial biomass, respiration rate, mycorrhizal associations, nematode communities, enzyme activities, fatty acid profiles and bioavailability of contaminants.

2.2. Physical Indicators of Soil Fertility and Soil Quality

Physical and chemical indicators are essential for assessing soil fertility and soil quality (Moncada *et al.*, 2013). Soil physical properties include various attributes critical to understand soil behavior and functionality. These include particle size distribution (texture), particle arrangement (structure), void volume and stability (porosity), amount of solids within a specified volume (density), movement of water into and through the soil (infiltration and hydraulic conductivity), plant and microbial water availability (available and residual water capacity), the amount of heat required to raise temperature of a unit mass of soil by 1°C (heat capacity), gaseous concentrations in soil atmosphere (soil air) and susceptibility of soil to erosion. Together, these properties influence the capacity of soil to support plant growth and sustain ecosystem functions (Lal, 2011).

These fundamental properties strongly influence ecological processes such as gaseous emissions, elemental cycling, hydrologic cycle, net primary productivity, energy budget and biodiversity. They also impact pedological processes like soil formation, Water retention and transmission, illuviation and leaching, humification, horizonation and transformation, as well as agronomic factors such as soil productivity, soil quality, resource use efficiency, soil degradation, resource use and adaptation to climate change. These interactions affect ecosystem services and ecological processes at soilscapes, landscapes and watershed scales (Roynolds *et al.*, 2002).

2.2.1. Soil Texture

Soil texture is the measurement of the proportion of sand, silt and clay inside a layer of soil. (Tabor *et al.*, 2017). It affects a variety of physical and chemical characteristics of the soil such as water infiltration and retention, nutrient absorption and aeration, root penetration, plant nutrition status, microbial activity, organic matter content and decomposition (Gupta, 2004). Soil texture plays a pivotal role in influencing various soil properties and growth and activity of soil organisms including plants (Osman, 2012). Sandy soils, known as light-textured soils are loose, friable and easy to work in both moist and dry conditions. They absorb water rapidly and drain it quickly with low concentrations of nutrients and poor moisture retention, low buffer and cation exchange capacities and rapid permeability. On the other hand, clay soils referred to as heavy-textured soils are compact and stiff. They are sticky when wet and hard when dry and require much energy to work both in wet and dry conditions (Osman, 2012). The bulk density of soil is highly influenced by soil texture (Martin *et al.*, 2017). It also plays a pivotal role in improving soil quality by creating isolated microhabitats that support the diversity and abundance of microorganisms. These microhabitats enhance microbial activity, contributing to better soil health and functionality (Abraham *et al.*, 2019). Soil texture significantly affects microbial activity because it directly influences the temperature and moisture content of the soil (Vinhal-Freitas *et al.*, 2017).

2.2.2. Soil Structure

Soil structure refers to the size, shape and arrangement of solids and voids as well as continuity of pores which collectively affect the capacity of soil to retain and transmit fluids and organic and inorganic substances, and ability to support vigorous root growth and development (Lal, 1991). It defines the network of pores and thereby porosity, water retention and aeration, and has a key function in stabilization of soil organic matter (Hoffland *et al.*, 2020). Favorable soil structure and high aggregate stability are essential for improving soil fertility and soil quality (Bronick and Lal, 2005). They enhance agronomic productivity by enhancing porosity and decreasing susceptibility of soil to erosion.

The decline in soil structure is increasingly recognized as a form of soil degradation (Chan *et al.*, 2003) and is often related to land use and soil or crop management practices. Soil structure influences soil water movement and retention, erosion, crusting, nutrient recycling, root penetration and crop yield (Bronick and Lal, 2005). This in turn threats the soil fertility and soil quality through causing the changes on other soil attributes. Externalities such as runoff, surface- and ground-water pollution and CO_2 emissions are influenced by soil structure (Bronick and Lal, 2005).

2.2.3. Bulk Density

Bulk density is commonly assessed to characterize the state of soil compactness in response to land use and soil management practices (Hakansson and Lipiec, 2000). It is determined by dividing the soil's dry weight by its volume, expressed in g/cm^3 (NRCS, 2011). Soil bulk density influences several soil properties, including infiltration, available water capacity, soil porosity, rooting depth, soil microorganism activity, root proliferation and nutrient availability (Indoria *et al.*, 2020). An increasing bulk density implies a decrease of macro-pores and an increase in meso and micro-pores and the resultant changes impacted on hydraulic conductivity (Fuentes *et al.*, 2004; Horn and Smucker, 2005). It is also utilized to express physical, chemical and biological measurements of soil on a volumetric basis for soil quality assessment and comparisons between management systems. Bulk density is a key indicator of soil quality and frequently used in different predictive models for evaluating soil quality (Fernandez *et al.*, 2019; Lema *et al.*, 2019).

2.2.4. Soil Water Content

Soil water content refers to the amount of water present in the soil. It plays a crucial role in regulating the soil temperature, facilitating the movement of chemicals, supporting plant growth and contributing to groundwater recharge (Sumon *et al.*, 2018). The amount of water in the soil determines how well nutrients are absorbed and it is also much related to its texture and structure (Yennawar *et al.*, 2013). The soil moisture commonly depends on void ratio, particle size, clay minerals, organic matter and ground water condition (Yennawar *et al.*, 2013). Compared to sandy soils, clayey soils typically contain more water due to their high porosity (Williams *et al.*, 2005). Excess water reduces the rate of oxygen diffusion in the soil which causes a decline in the activities of aerobic soil microbes but could increase the activity of anaerobic soil microbes (Yan *et al.*, 2015).

2.3. Chemical Indicators of Soil Fertility and Soil Quality

Soil chemical properties are the most significant factors that determine the nutrient supply of soil to plants and microbes. The processes which lead to soil creation and soil fertility are influenced by chemical reactions. Minerals derived from soil parent materials are chemically responsible for time-release of elements that undergo various changes in the soil (Lilienfein *et al.*, 2000). Most indicators of soil chemical quality measure dynamic soil properties i.e. properties that change over time and with management. These indicators are used to guide management decisions over the period of a rotation. It is important to monitor these indicators as they can act as constraints to yield, restricting crop growth and preventing the yield potential from being achieved (Elizabeth, 2023).

2.3.1. Soil Reaction

Soil pH is a measure of the concentration of hydrogen ions in the soil solution, determining its acidity and alkalinity. The scale ranges from 1 (most acid) to 14 (most alkaline), with most soils normally falling between pH 3 and 8 (Elizabeth, 2023). It is considered to be a significant soil property as it determines the nutrient accessibility and the physical condition of the soil controlling the diversity of microbes in soil (Abraham *et al.*, 2019). The soil pH influences the buffering capacity and quality of organic substances in the soil (Usharani *et al.*, 2019). A decline in soil pH has been widely reported to reduce microbial growth and activity (Geisseler and Scow, 2014). Baath and Anderson (2003) showed that, a rise in soil pH causes an increase in microbial biomass. Elizabeth (2023) revealed that acidic soils can limit microbial activity, reduce the availability of essential nutrients and lead to aluminum toxicity in the subsurface. This toxicity hampers root growth, restricting the ability of plant to access essential water and nutrients.

2.3.2. Electrical Conductivity

The concentration of soluble salts in the soil solution is measured by the electrical conductivity (EC) of the saturation extract, commonly expressed in deciSiemens per metre (dS/m) (Elizabeth, 2023). Salinity refers to the accumulation of soluble mineral salts in the soil (Tanji 2002). Excess amounts of salts present in soil can affect the soil productivity (Yan *et al.*, 2015). Moreover, soil salinity influences the soil microbial diversity (Yan *et al.*, 2015; Zhao and Xu, 2016). Excessive salt content increases the osmotic potential of soil water, drawing water out of soil-dwelling microbial cells which can lead to their death, ultimately reducing soil microbial diversity as well as soil quality (Yan *et al.*, 2015). Sodic Salinity also deteriorates soil structure, contributing to soil degradation (Abraham *et al.*, 2019).

2.3.3. Soil Organic Matter

Soil Organic Matter (SOM) is consisting of plant and animal residues at various stages of decomposition, cells and tissues of soil organisms and substances they synthesized. It positively influences soil physical and chemical properties, as well as the capacity of soil to provide essential ecosystem services (Chetan *et al.*, 2019). Soil Organic Matter (SOM) is a key attribute of soil and environmental quality, acting as both nutrient sink and source for plants and microbes. Despite its minor contribution to the total mass of soils, it significantly influences physical, chemical and biological functions. Organic matter incorporated into the soil improves soil structure, porosity, aggregation and bulk density, while affecting water, air and heat transmission and soil strength. Through organic matter decomposition, it releases essential nutrients such as N, P, and S into the soil, enhancing nutrient availability (Dordrecht, 2008).

Oldfield *et al.* (2018) have reported that high concentration of SOM causes an increase in water holding capacity of the soil. Soil Organic Matter (SOM) acts as a buffering agent that limits sudden chemical and temperature changes occurring in the soil (Mohammadi *et al.*, 2011). Also, it helps in enhancing the biological activity and diversity present in the soil (Norris *et al.*, 2018). Thus, SOM serves as an important indicator for determining soil fertility and soil health (Obalum *et al.*, 2017).

2.3.4. Total Nitrogen

Nitrogen is considered to be an essential soil nutrient as it limits the productivity of soil by affecting various soil properties, plant growth and microbial activities of soil (Li *et al.* 2019b). It is very abundant in the atmosphere as di nitrogen gas (N_2), but it is largely inaccessible to most organisms in this form. This makes nitrogen a scarce resource and often limiting primary productivity in many ecosystems. Nitrogen becomes available to primary producers like plants only when it is converted from di nitrogen gas into ammonia (NH_3) (Bernhard, 2010). Soil total nitrogen (STN) is the major determinant and indicator of soil fertility and quality in an agricultural ecosystem and closely related to soil productivity (Al-Kaisi *et al.*, 2005).

2.3.5. Available Phosphorus

Phosphorus is an essential nutrient for terrestrial productivity and plays an important role in the conversion of carbon biomass into soil organic matter by influencing microbial activity, enzyme production and energy transfer in terrestrial ecosystems (Filippelli, 2017). Soil phosphorus along with nitrogen acts as a key indicator of soil fertility. It affects various soil properties, plant growth and microbial activities, thereby affecting the overall structure and functioning of soil ecosystem (Filippelli 2017; Li *et al.*, 2019b). Phosphorus in the soil exists in many forms, with the organic form being the most available. However, plants unable to take this organic form of phosphorus (Filippelli 2017). To become available to plants, organic phosphorus must undergo mineralization, converting it into inorganic forms like phosphate that plants can utilize. It is also major determinant and indicator of soil fertility and quality.

2.3.6. Available Potassium

Potassium is one of the important macronutrients which greatly impacts crop growth, yield and quality of produce. Besides, its essential role in crop nutrition, it is also crucial for soil health as it provides stability to various soil minerals (Debarup *et al.*, 2019). Potassium plays a significant role in the advancement of plant roots (Jaiswal *et al.*, 2016), increases crop yield and improves tolerance in various biotic and abiotic stresses. It also helps to activate enzymes for metabolic processes in plants (Jaiswal *et al.*, 2016; Sattar *et al.*, 2019). Potassium-solubilizing bacteria (KSB) include a wide range of bacteria such as *Pseudomonas sp.*, *Burkholderia sp.*, *Acidithio bacillus ferro oxidans*, *Bacillus mucilaginosus*, *Bacillus edaphicus*, *Bacillus circulans* and *Paeni bacillus sp.* that have been found to release mineral bound potassium from the soil (Jaiswal *et al.*, 2016). Inadequate potassium in the soil causes reduction in product yield of crops and quality of crops, reduces root development in plants (Jaiswal *et al.*, 2016), affects nitrogen fixation ability of plants by affecting the microbial community and affects various physiological and metabolic processes of plants (Jaiswal *et al.*, 2016; Singh and Pathak, 2018).

2.3.7. Cation Exchange Capacity

Cation exchange capacity is the ability of soil to absorb cations from the soil and imparts a negative charge to the soil (Graber *et al.*, 2017). It also provides buffering capacity against pH change in the soil (Rahal and Alhumairi, 2019). Cation exchange capacity acts as a sensitive indicator for determining nutrient holding capacity of the soil, its fertility and long term productivity (Graber *et al.*, 2017; Moral and Rebollo, 2017). Soils with high CEC also have high clay content and high water holding capacity (Moral and Rebollo, 2017; Rahal and Alhumairi, 2019). Also, soil with high CEC requires less application of fertilizers (Shiri *et al.*, 2017). Cation exchange capacity increases with the increase in pH due to enhanced negative charges on soil colloids (Graber *et al.*, 2017). Soils with higher CEC have high organic matter and soils with high organic matter also have higher microbial diversity and abundance (Xu *et al.*, 2016).

2.3.8. Extractable Micronutrients

Micronutrients though present in small percentage in plants, are critical for their growth. Most are used in enzymes rather than structural components of the plant (Amber, 2023). According to the same author, deficiencies can occur under extreme conditions, such as very high or low pH values or peat soils. These deficiencies are addressed with small quantities of micronutrients, which can be added through materials like manure or composts, depending upon soil analysis.

There are eight micronutrients that are essential for plant growth. These include boron, zinc, manganese, molybdenum, iron, copper, chlorine and nickel (Amber, 2023). All micronutrients are needed in small amounts so when soils contain too much of them, toxicity can occur. They are influenced by LULC types and slope position and directly they affect the soil fertility and soil quality by influencing the change on soil quality indicators (Amber, 2023).

2.4. Biological Indicators of Soil Fertility and Soil Quality

Soil biological indicators reflect the living component of the soil assess soil quality by analyzing soil functions, just like physical and chemical indicators do (USDA, 2014). These indicators are dynamic soil properties that are highly susceptible to chemical pollutants, natural disturbances and land management practices (USDA, 2014). Numerous organisms that live in the thin soil surface layer are vital to the decomposition of organic matter, the nutrient cycling, the degradation of pollutants and maintaining the stability and structure of the soil. The biological soil indicators encompass the properties linked with the soil biological activity, such as microbial biomass carbon, soil respiration and mesofauna (e.g., earthworms, nematodes and arthropods) (Marriot and Wander, 2006). In addition, they incorporate biological processes that reflect the functional dynamics of soil ecosystems, such as CO_2 production, nitrogen mineralization and enzyme activity (Tejada *et al.*, 2006).

2.4.1. Earthworms

Earthworms are essential to the functioning of terrestrial ecosystems, enhancing soil health by promoting aggregate stability, improving water-holding capacity, porosity, root development and infiltration rates (Stockdill, 1982; USDA, 2014). Based on their habitat, earthworms are divided into three ecological groups (USDA, 2014): litter-dwellers inhabit surface organic layers, consuming plant residues and frequently disappearing in plowed, litter-depleted soils. Because of their different feeding and burrowing habits; mineral soil-dwellers occupy organic-rich topsoil, digging narrow burrows and feeding on a mixture of soil and plant matter; and deep soil-burrowers (night crawlers) dig extensive vertical tunnels into deeper soil, carrying surface plant debris underground for decomposition, each group contributes in a unique way to improving soil structure, organic matter distribution, and nutrient cycling. Earthworms and their function in soil are becoming better understood. From the micro-scale within a soil profile to the field scale or landscape scale, the research techniques are a crucial tool for enabling meaningful analysis (Maria *et al.*, 2010).

2.4.2. Soil Enzymes

Enzymes are vital catalysts in biological processes; they also have a big impact on soil, greatly enhancing its stability and overall health (Sahil *et al.*, 2023). Microorganisms are the main source of soil enzymatic activity, which can take the form of free, intracellular, or cell-associated enzymes. Soil enzymes perform biochemical roles in the overall process of the organic matter decomposition by catalyzing a number of reactions that are essential for the life processes of soil microorganisms, stabilizing soil structure, breaking down organic waste, forming organic matter, and cycling nutrients (Kandeler *et al.*, 2006).

Eldor (2007) reports that enzymes are good indicators, because they are closely related to organic matter, physical characteristics, microbial activity and biomass in the soil; and they provide early information about changes in quality and more quickly assessed. Determination of enzyme activity is required the strict laboratory conditions with the special attention paid to temperature regulation, incubation duration, pH buffer, solution ionic strength and substrate concentration (Gutiérrez *et al.*, 2008). According to Das and Varma (2011), the soil enzymes such as Cellulose, Phenol oxidase, Dehydrogenase, Urase, Amidase, Phosphatase, β-glucosidase and Arylsulphatase have important biochemical roles in overall organic matter breakdown process in the soil system.

2.4.3. Particulate organic matter

Particulate organic matter (POM) is a biologically and chemically active fraction of soil organic matter consisting of particles ranging in size from 0.053 mm to 2 mm that is thought to be a part of the labile pool of SOM, which means it decomposes readily (USDA, 2014). POM plays a crucial role in soil functions, such as nutrient cycling, aggregate stability and water infiltration.

2.4.4. Microorganisms

Microorganisms are widely used as soil quality indicators. There are many different microbial taxa in soil, and they exhibit a wide range of metabolic activities (Parkinson and Coleman, 1991). A number of ecological factors, including plant diversity, soil organic matter content, moisture and climate change, affect soil microbial biomass, making it a more sensitive indicator than that of superior organisms (Maria *et al.*, 2010). Microorganisms are essential for the cycling of nutrients and energy flow (Li and Chen, 2004) and providing information on the effects of intercropping, the addition of organic matter, management practices (Shannon *et al.*, 2002) and tillage operations on soil structure and stabilization. In addition to biological N_2 fixation and P solubilization in the rhizosphere, microorganisms such as fungi, mycorrhizal fungi, microbial interactions and other beneficial symbioses of the host plant can increase the efficiency of nutrient use by increasing the surface area of the roots (Maria *et al*., 2010).

2.5. Effects of Land-Use Land-Cover Types on Soil Fertility and Soil Quality

Land use/land cover types highly affect the soil fertility and quality by changing the physical, chemical and biological indicators of the soil. These soil indicators are particularly sensitive to changes in soil conditions, highlighting their dynamic nature (Moffat, 2003). Moreover, variations in soil indicators depend on the specific LULC types and the plant restoration measures (Moffat, 2003).

Previous studies revealed that severe soil quality deterioration caused by factors such as soil erosion, changes of LULC types, deforestation and overgrazing (Moges *et al.*, 2013, Yitbarek *et al.*, 2013 and Demboba, 2005). The conversion from forest to another agricultural use leads to a significant reduction and changes in soil qualities (Tesfahunegn, 2016). Studies have also reported the significant influence of changes of LULC types on soil quality indicators (Delelegn *et al.*, 2017, Ishaq *et al.*, 2015 and Pham *et al.*, 2018). A study conducted in Blue Nile Basin of Ethiopia showed that the changes in land use and management systems significantly influenced the key soil quality indicators (Tefer *et al.*, 2016). Studies elsewhere (Moges *et al.*, 2013; Yitbarek *et al.*, 2013; Delelegn *et al.*, 2017; Ishaq *et al.*, 2015; Pham *et al.*, 2018; Tefer *et al.*, 2016) demonstrated that changes in LULC types had a major impact on the soil fertility and quality.

2.6. Effects of Slope Position on Soil Fertility and Soil Quality

Topography as a major soil-forming factor can cause significant changes in soil properties over very short distances (Araba, 2021). Elevation, slope and aspect are the primary topographical factors that can affect soil development. Various slope positions exhibited significant differences in certain soil physicochemical properties, including soil texture, bulk density, organic carbon, total nitrogen, cation exchange capacity and exchangeable bases (Khormali *et al.*, 2007). Slope position can influence soil nutrient availability, with Chen *et al.* (2002) reporting elevated levels of Fe, Mn, Cu and Zn in soils located at upper slope positions.

Topography and land use types are crucial determinants of soil property variability, with slope position acting as a primary controller of hydrological and soil processes at the landscape level (Araba, 2021). Steep slopes and land use practices drive soil erosion in Ethiopia's primarily mountainous terrain, which coupled with unsustainable farming practices worsens decreased crop yields and causes widespread soil resource degradation (Araba, 2021). According to Weldemariam *et al.* (2020), the analysis of variance showed that the significant variation among the selected soil physicochemical properties due to variation in the land use types and slope factors; bulk density, total porosity, AV.P, soil pH, EC, SOM, SOC, TN and C:N were found strongly dependent on land use, slope positions and their interactions. Furthermore, Bahilu *et al.* (2014) reported that, OC, TN, C:N AV.P, CEC, exchangeable bases, ESP and PBS were significantly lower in the soil under cultivated land at upper slope positions than in respective slope positions of the other two land use types.

2.7. Soil Fertility Status in Ethiopia

A reduction in soil fertility is becoming one of the major challenges for developing sustainable agriculture in order to feed the rapidly growing population in Ethiopia (Siraji *et al.*, 2015). This is explained by the extremely rough terrain, greatly varied topography and mountainous landscape which further govern the variations in soil parent materials, agro ecological zones and LULC types within a given area (Getachew and Heluf, 2007). Assessing the fertility of the soil is a valuable tool for raising crop yields and productivity in Ethiopia (Gete *et al.*, 2010). Ethiopian soil's basic characteristics make it difficult to manage in an agricultural plot because of the country's topography, climate, variety of soil types, and anthropogenic activities like overgrazing and deforestation (Ashenafi *et al.*, 2010). Soil chemical conditions like soil pH, salinity, cation exchange capacity (CEC) and nutrient concentration together with soil physical property like particle size distribution (texture) and bulk density highly influence nutrient availability (Alley and Vanlauwe, 2009). Therefore, monitoring physical and chemical characteristics of soil provides information on how the soil reacts to agriculture practices. It provides insights into soil fertility trends, highlighting potential declines and identifies the relationship between soil fertility and crop conditions (Chillot and Hassan, 2009).

Numerous studies in Ethiopia surveyed various soil nutrients, focusing primarily on macronutrients at the watershed level. Extensive analyses of macronutrients across the soils of the country were carried out in the 1950s and 1960s, initially by Alemaya College of Agriculture and later by the Institute of Agricultural Research at Holetta, Werer and Bako research centers (Gete *et al.*, 2010). However, these studies neglects soil micronutrients and were limited in geographic scope, making it impossible to provide comprehensive spatial information about Ethiopia's soil nutrient status (Gete *et al.*, 2010).

Although many studies on soil and related topics were carried out in Ethiopia and published in various forms, these efforts were dispersed and site-specific, so failing to provide a comprehensive picture of Ethiopia's soils (Gete *et al.*, 2010). Simply developing a generalized soil map does not guarantee increased crop production and productivity without complete soil fertility assessment and mapping (Gete *et al.*, 2010). Furthermore, the absence of regular assessments of soil fertility in Ethiopia becomes the other main problem that limits optimum crop production (ATA, 2013). Considering such and other constraints, the EthioSIS-ATA in collaboration with different stakeholders, was recently initiating a rapid development program on the assessment of the soil resources of the country. This initiative aims to establish a national soil resources database, assess the nutrient status of agricultural lands and produce soil fertility map of many districts in the country. The goal is to come up with solid, evidence-based and targeted recommendations for fertilizer applications and other soil management practices (ATA, 2013).

Integrated soil fertility management (ISFM) is a collection of practices that inevitably involve the use of inorganic fertilizers, organic inputs and improved germplasm, along with the understanding of how to modify these practices to local conditions, in order to maximize the agronomic use efficiency of the applied nutrients and increase crop productivity (Vanlauwe *et al.*, 2010). The German Agency for International Cooperation (GIZ) initiated the "Integrated Soil Fertility Management Project" in Ethiopia in 2015, focusing on the three highland regions of Amhara, Oromia, and Tigray. Through group-based learning approach, this project creates and advances locally tailored ISFM practices (Davis *et al.*, 2012). The promotion of ISFM options into Ethiopia's agricultural system has recently involved a number of projects, such as the Wageningen-EIAR Integrated Nutrient Management project, MoARD/SG 2000 Conservation Agriculture trials, AGRA-EIAR ISFM project, GIZ-ISFM project, and N2Africa (GIZ, 2020). In order to sustainably improve soil fertility, productivity and rural residents' quality of life, ISFM is now a component of the country's "Soil Health and Fertility Improvement Strategy" (MoANR, 2017).

In order to address major soil fertility bottlenecks and transform the agriculture sector, the MoA and Ethiopia's Agricultural Transformation Agency (ATA) created the Soil Health and Fertility Roadmap in 2011 and 2012 (Erkossa *et al.*, 2022). This roadmap aims to improve soil health, increase yield, and raise smallholder farmers' incomes by recommending fertilizer based on soil tests through the Ethiopian Soil Information System (EthioSIS) program. The 96% of Ethiopian soils are either acidic or alkaline, according to an ATA soil fertility status survey, and they are deficient in macro- and micronutrients (such as S, Zn, B, Cu, and Fe) in addition to N and P (EthioSIS, 2014). The import of blend fertilizers was started, followed by the establishment of blending factories, in order to replace the import. However, the effort hasn't been as successful as anticipated thus far. Many soil scientists strongly disagree with the current widespread use of blend fertilizers without adequate validation of the suggested blends, even though there is agreement that a new recommendation incorporating additional macro- and micronutrients is necessary (Erkossa *et al.*, 2022). Results from the blend fertilizers' on-station and on-farm verification tests were not entirely consistent. Increased crop yield and agronomic efficiency (Bizuwork and Yibekal, 2020); also both neutral and negative results were reported (Eyasu *et al.*, 2020), suggesting that the recommendation needs to be adjusted to fit the target sites' unique biophysical and socioeconomic context. Thus, after harmonized and standardized field trials, the new recommendation needs to be validated and further refined. Understanding how fertilizer application affects crop yield under various topographic, climatic and management circumstances is necessary to create fertilizer recommendations that are site and context-specific (Erkossa *et al.,* 2022).

2.8. Soil Quality Index

Soil quality index (SQI) is a useful tool for assessing soil quality (Nabiollahi *et al.*, 2018). Direct soil quality measurement is not possible, but it can be inferred using indicators. These indicators comprehensively represent the physical, chemical and biological attributes of the soil (Karlen *et al.*, 2003). There are numerous ways to evaluate the quality of soil, which simplify complex datasets with several variables by reducing dimensionality, making evaluation more accurate and precise. However, selecting appropriate soil quality indicators remains a difficult problem to be solved. The indicators are expected to have an important effect on soil function and evaluation results (Nakajima, 2015). Thus, the key step in evaluating SQI is to choose quantitative and qualitative indicators in a scientific manner and create an appropriate minimum data set (MDS).

2.8.1. Minimum Data Set

Selection of a minimum dataset from a larger set of soil quality indicators is a necessary step in soil quality assessments in order to overcome time and cost constraints and avoiding issues of collinearity. More indicators can complicate the relationships between management practices and indicators and increase collinearity (O'Sullivan *et al.*, 2017). For these reasons, the number of soil quality indicators that is actually analyzed on a given set of samples needs to be reduced to a minimum dataset. There are two main methods to select the minimum data set for soil quality index such as expert opinion and statistical data reduction methods (NRCS, 2011). Expert opinion requires expert knowledge of the system and the management goals dictate the soil functions of interest which in turn, suggest related indicators. Statistical data reduction focused on the multivariate techniques such as principal component analysis (PCA), redundancy analysis (RDA), discriminant analysis and multiple regressions (Shukla *et al.*, 2006).

2.8.2. Computation of Soil Quality Index

The soil quality index indicates the relative soil quality available under different land use/land cover types (Rakesh and Kottapalli, 2012). The soil quality indexing process involves three interrelated steps that work together to evaluate the soil quality. The first step involves the selection of indicators to form the MDS. This selection can be based on expert opinion, insights from previous studies or Principal Component Analysis (PCA) methods. Once the indicators are chosen, their scores are transformed into common measurement scale using linear or nonlinear scoring methods to enable quantification of all indicators. Finally, the transformed scores are combined into soil quality index through methods such as additive, weighted additive or decision support system (Rakesh and Kottapalli, 2012).

3. MATERIALS AND METHODS

3.1. Description of Study Area

3.1.1. Location

The study was conducted at Maya Guddo subwatershed in Maya City, East Hararghe Zone of Oromia National Regional State. The study area is adjacent to the Kurfa Chele district to the south, Kersa district to the west, Dire Dawa City Administration to the north and Kombolcha district to the east. The geographical location of the study area lies between 9°22'26''-9°23'30''N and 41°59'41''-42°01'05''E. It is positioned between Addis Ababa and Harar city, at a distance of 505 km from Addis Ababa to the east and 20 km northwest of Harar city. The altitude of the district ranges from 1400 to 2340 meters above sea level with the highest points including Dof and Jeldo (SEP, 2006).

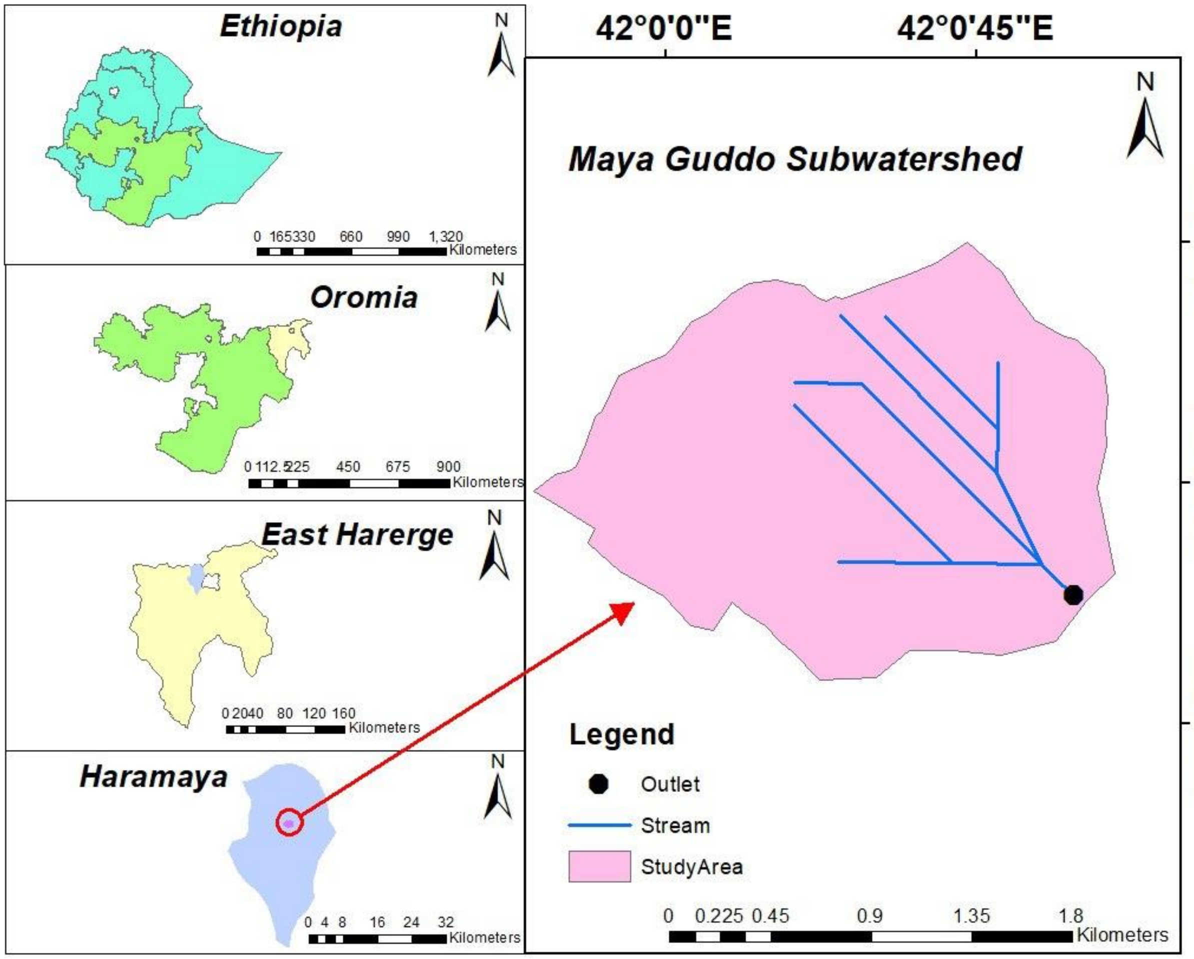

Figure 1: Map of the study area

3.1.2. Climate

Agro-ecologically the area is classified as semi-arid tropical belt of eastern Ethiopia and characterized by a sub-humid type of climate (Usmael *et al.*, 2018). Data from Ethiopian meteorology institute indicate that the mean annual (1994-2023) rainfall of the area is about 818.26 mm. It is characterized by a bimodal rainfall distribution pattern. The short rainy season locally, called *Badheessa*, usually starts in March and extends to May and the long rainy season called *Ganna* stretches from the end of June to September (Kibebew, 2014). The mean monthly minimum temperature ranges between 12.48 ℃ in December and 16.99 ℃ in April, while the mean monthly maximum ranges between 26.45 ℃ in December and 30.00 ℃ in March.

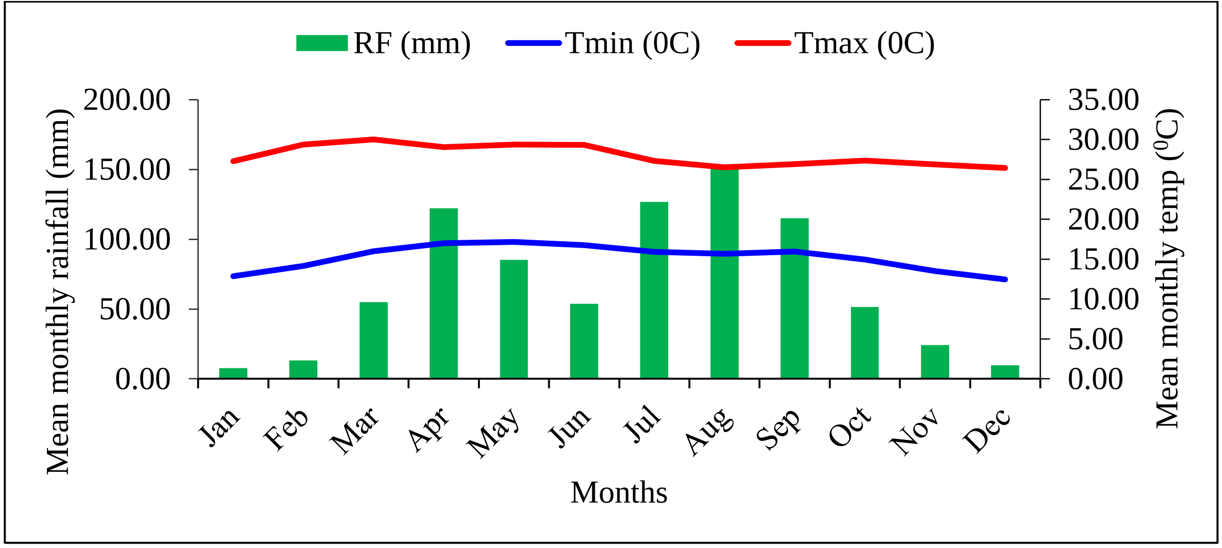

Figure 2: Mean monthly rainfall, monthly maximum and minimum temperatures of the study area (1994 - 2023) based on the records from Ethiopian Meteorological Institute

3.1.3. Geology

Hararghe Zone is generally overlain by limestone and sandstone deposits which formed during the Triassic period of the Mesozoic era and during the Jurassic and Cretaceious Period of the same era (Heluf and Yohannes, 1997). The Hararghe Highlands including Lake Haramaya Watershed lie over the crystalline bedrock of ancient Gondwana continent which broke apart at a much later time (Solomon, 2002). The Precambrian lay as pen plains below sea level for a longer period of time was formed by the hard rocks of the Gondwana continent, granite and genesis, which led to the deposits of extremely old sedimentary rocks in the eastern region (Solomon, 2002). These ancient sedimentary rocks were mainly limestones and sandstones; the sandstones were formed in the deeper areas of the sea, while the limestones were deposited in the shallower parts. The Precambrian metamorphic rock, granite and to a lesser extent gneiss and mica schists, are particularly exposed on the surface throughout Haramaya watershed area (Tamire *et al.*, 1986). The steeper slopes have a large rounded boulders of granite rocks exposed on the surface; this is a clear indication of severe erosion that has washed away the surface soil and exposed weathering granite boulders on the land surface.

3.1.4. Topography and Soils

The topography of the district varies from nearly level land, which represents the plains and plateau areas, to moderately steep and undulating land that characterizes the medium to high gradient hills (Kibebew, 2014). The landform is highly dissected with many drainage networks. As a result, there are many mini-watersheds that have their own peculiar characteristics in terms of hydrology, geology and, thus, major types of soils (Kibebew, 2014).

According to Tamire (1986), the main categories of soil are Leptosols, Regosols, Cambisols, Vertisols, and Fluvisols. These soils form a typical toposequence in which the Leptosols and Regosols occupy mostly the steeper slopes, while the other soil types occur in the gentle to low-lying landscapes of the watershed.

3.1.5. Farming Systems

The major crops cultivated under rain fed conditions are sorghum (*Sorghum bicolor L.*), maize (*Zea mays*) and various pulse crops. Dual season crop production is also practiced both under rain-fed and irrigation. Vegetables such as potato (*Solanum tubersum*), lettuce (*Lactuca sativa*), onion (*Allium cepa*) and Khat (*Catha edulis*) are dominantly cultivated in the district (Kibret *et al.*, 2022). The common cash crops produced under irrigation in the area are; potatoes, head cabbage, leaf cabbage, lettuce, hot pepper, carrot, shallot, beat root and leek (baro). These are important crops following khat (Kibret *et al.*, 2022). Khat (*Catha edulis*), vegetables and fruits are vital cash crops in the study area (SEP, 2006). Livestock also plays an integral role in agricultural system; with common domestic animals that include cattle, sheep, donkeys, goats and poultry. These animals provide meat, milk, hides, manure for soil fertility maintenance and the source of income for farmers (SEP, 2006).

3.1.6. Land Use/Land Cover Types

A survey of the land use in Haramaya district shows that 36.1% is arable or cultivable, 2.3% pasture, 1.5% forest and the remaining 60.1% is considered built-up, degraded or otherwise unusable (SEP, 2006).

Table 1: Description of the dominant land-use land-cover types within Maya-Guddoo subwatershed

No.	Land-use land-cover types	Brief description
1.	Cultivated land use type	This land use type utilized for growing various cash and staple crops such as wheat, barley, maize, sorghum and other grains, and vegetables, selected according to local demands and seasonal conditions. Farmers primarily use synthetic fertilizers (DAP and Urea) to increase yields. Low soil organic matter levels in this land use type, mostly as a result of little crop residue being retained after harvest, because it is used for other things like animal feed, fuel wood and additional revenue sources.
2.	Grazing land cover type	This category characterized by natural grassland, maintained primarily for livestock foraging.
3.	Khat land use type	This land use type is defined by the purposeful cultivation of *Catha edulis,* a perennial shrub which is grown for its stimulating leaves. Khat crop is the vital cash crop in the study area.

3.2. Soil Quality Indexing Process

3.2.1. Indicator Selection

Yared (2018) states that the general criteria for selecting soil quality indicators include the indicator's impact on soil productivity, its sensitivity to changes in the environment, the cost and ease of sampling and the method of analysis of the indicators to be chosen. The selection of indicators for this study considered their impact on soil productivity, relevance to soil functionality, spatial and temporal variability, scientific validity, long-term monitoring and compatibility with the agro-ecology of study area and existing standards. Reviews of prior studies and expert opinion were used to select the MDS of indicators. The soil indicators used as indicators of soil quality are presented as follows in Table 2.

Table 2: Soil quality indicators and the values of scoring function for evaluating the soil quality indices in the study area.

Source of limits	Scoring curve	Threshold Lower	Upper	Baseline	Optimum	Slope at baseline	Source of Threshold
Clay (%)	More is better	0	30	15	----	0.266	(Gebreyesus, 2014)
Sand (%)	Optimum is better	0	60	L-30 U-50	36	0.44	(Gebreyesus, 2014)
Silt (%)	More is better	0	38	19	---	0.249	(Gebreyesus, 2014)
Porosity (%)	Optimum is better	20	80	L-40 U-60	50	0.1280	(Karlen *et al.*, 1994).
Bulk density (g/cm^3)	Less is better	1.0	2.2	1.5	1.2	-2.62	(Harris *et al.*, 1997).
FC (%)	More is better	15	25	20	-	-2.50	(Ahmed *et al.*, 2021).
AWHC (%)	More is better	2	10	4	-	0.198	(Gregory *et al.*, 2000).
pH(H_2O)	Optimum is better	4.5	9.5	6.5	5.3	1.3012	(Karlen *et al.*, 1994).
CEC (cmol(c) kg^{-1})	More is better	6	46	20	---	0.245	(Gebreyesus, 2014)
OC (%)	More is better	1	6.5	3.5	---	1.046	(Kay and Angers, 1999)
TN (%)	More is better	0.05	0.54	0.34	---	25.408	(Gebreyesus, 2014)
AV.P(mg/kg)	More is better	5	29	15	---	0.433	(Mausbach and Seybold, 1998).
Fe (mg/kg)	Optimum is better	10	50	L-20 U-40	26	0.577	(Harris *et al.*, 1997).
Zn (mg/kg)	Optimum is better	2	20	L-10 U-18	14	0.855	(Mausbach and Seybold, 1998).

Soils at or below the threshold values are prone to structural destabilization, erosion and low productivity; so the scoring value is 0. Soils at or beyond this values no further increase in productivity or decrease in erosion rate are achieved the upper threshold; values at and above this level thus receive a score of 1.0. Values receive a score of 0.5and are generally regarded as the minimum target values.

3.2.2. Indicator Interpretation

The chosen indicators were converted using a linear technique into dimensionless scores between 0 and 1 in accordance to Diack and Stott (2001). The "more is better," "less is better," or "optimal is better" functions were used to assign scores between 0 and 1 to the indicators that were part of the MDS. After determining the linear relationship of the expected response, the scores were allocated according to soil function. According to the baseline, lower and upper threshold values, the score for each indicator was determined. The baseline value of the soil property corresponds to the score equal to 0.5. In general, baseline values are thought of as the lowest possible target value. When the measured soil property is at its most favorable level, the score equals one (upper threshold); when it is at an unacceptable level, the score equals zero (lower threshold) (Diack and Stott, 2001).

$$\boldsymbol{f(x) = \begin{cases} 0.1 & X \leq L \\ 0.9 * \frac{X-L}{U-L} + 0.1 & L \leq X \leq U \\ 1 & X \geq U \end{cases}} \tag{1}$$

$$\boldsymbol{f(x) = \begin{cases} 1 & X \leq L \\ 1 - 0.9 * \frac{X-L}{U-L} + 0.1 & L \leq X \leq U \\ 0.1 & X \geq U \end{cases}} \tag{2}$$

Where, f(x) is the linear score; x is the soil property value; and L and U are the lower and upper threshold values, respectively. The first equation was applied to the "more is better" scoring function, while the second equation was utilized for the "less is better" function. The "optimum is better" function was evaluated as "more is better" for the increasing part and as "less is better" for the decreasing part.

3.2.3. Soil Quality Indexing

According to Masto *et al.* (2008), the process of integrating soil quality indicators into a SQI involved calculating the score for each indicator; these scores were then summed for each LULC type and the total was divided by the number of indicators.

$$\mathbf{SQI} = \frac{\sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{Si}}{\boldsymbol{n}} \tag{3}$$

Where, SQI is the soil quality index, Si is the linear scored value of individual indicators and n is the number of indicators included in the dataset. The SQI value close to 1 refers to the best functioning soil, while zero (lower threshold) value refers to severely degraded soil.

3.3. Site Selection, Soil Sampling and Sample Preparation

Soil samples were collected from the fields under different LULC types across slope positions in 2024 before the land preparation for agricultural activities. A reconnaissance survey was conducted before the collection of soil samples, complemented by informal discussions with agricultural experts. These efforts aimed to identify the various LULC types, as well as the soil and land management history throughout the study area. The entire subwatershed area was split into three slope positions (upper, middle and lower) in order to identify the main LULC types (cultivated, grazing, and Khat) in the study area. Google Earth along with a digital elevation model (DEM, 30 x 30 m) was utilized to establish the preliminary boundaries of the subwatershed and to select temporary soil sampling sites across various LULC types. Subsequently, in situ field observations were conducted to accurately identify sampling land units under each LULC type and slope position. The sampling sites were geo-referenced using a GPS and the slopes of the sites were measured using a clinometer. Afterward, a total of 27 surface composite soil samples (9 from each LULC type) were collected from cultivated, Khat and grazing LC types across slope positions at a depth of 0-20 cm. For each composite sample, eight to ten sub samples were randomly collected using the quadrant method and thoroughly mixed on a plastic sheet to form approximately one kilogram of composite soil sample per sampling unit. Undisturbed soil samples were collected from the center of the quadrant from each sampling site by using core sampler for the determination of soil bulk density and soil water content at FC and PWP. Subsequently, the composite samples were packed and appropriately labeled in plastic bags and submitted to the soil laboratory of Haramaya University for the analysis of selected soil properties.

The disturbed soil samples were air dried, crushed using mortar and pestle and passed through a 2 mm sieve in the laboratory for soil properties except for soil OC and TN before analysis. For the assessment of organic carbon and total nitrogen, the soil size was further reduced to pass through 0.5 mm sieve. Undisturbed soil samples were used to measure bulk density and soil water contents.

3.4. Soil Laboratory Analysis

Soil particle size distribution was assessed using the Bouyoucos hydrometer method (Bouyoucos, 1962). Bulk density was determined from undisturbed soil samples using core sampler (Black and Hartge, 1986). Total porosity was calculated from soil bulk and particle densities as indicated below (Eq. 4).

$$f(\%) = \left(1 - \frac{\rho_b}{\rho_s}\right) \times 100 \tag{4}$$

Where: ρ_b is bulk density (g/cm^3), ρ_s is the average particle density, which is generally used as 2.65g/cm^3 (Weil and Brady, 2017), and f is total porosity in percentage. The pressure plate extraction method was utilized to measure the soil water retention capacity at FC (33 kPa) of undisturbed core soil samples and PWP (1500 kPa) of disturbed soil samples taken from core samples. Subsequently, the AWHC was calculated as the difference between water content at FC and PWP (Hillel, 1980).

The major chemical properties analyzed include Soil pH, EC, OC, CEC, TN, AV.P, Exchangeable bases (K, Na, Ca and Mg) and Extractable Micronutrients (Fe, Zn, Cu and Mn). Soil pH and EC were determined using a 1:2.5 soil to water ratio as described by Van Reeuwijk (1993). Organic carbon was analyzed through the wet oxidation method (Walkley and Black, 1934). Soil organic matter was estimated by multiplying the percentage of OC by a conversion factor of 1.724 ($\%OM = 1.724(\%OC)$). Total nitrogen and available phosphorus were determined using the Micro-Kjeldahl procedures (Kjeldahl, 1883) and Olsen method (Olsen *et al.,* 1954) respectively. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) in the soil were estimated by the ammonium acetate (1 M NH_4OAc at pH 7) extraction method. Calcium (Ca^{2+}) and Mg^{2+} in the extracts were determined using the atomic absorption spectrophotometer (AAS), while flame photometer was used to measure the contents of exchangeable K^+ and Na^+ (Rowell, 1994). Ammonium Acetate Method (1 M NH4OAc at pH 7) was used to measure the CEC in the soil. Percent base saturation was computed as the ratio of the sum of exchangeable bases to the CEC multiplied by 100. Extractable Micronutrients (Fe, Zn, Cu and Mn) were extracted by diethylenetriaminepenta-acetic acid (DTPA) method and read by using AAS.

3.5. Data Analysis

A descriptive statistics was used to assess the status and variation of selected soil properties across various LULC types and slope positions. The laboratory data were analyzed using two-way ANOVA of a factorial model in R (version 4.1.1) to evaluate the statistical differences in soil properties among different LULC types and slope positions. Tukey's Honest Significant Difference (HSD) test ($P \leq 0.05$) was used to compare means. The test provided the Minimum Significant Difference (MSD) value, which was used to determine whether differences between group means were statistically significant. A simple linear correlation analysis was conducted to calculate correlation coefficients (r) among and within various soil parameters across different LULC types and slope positions by using R software.

4. RESULTS AND DISCUSSION

4.1. Effects of LULC types and Slope Positions on Physical Properties of Soil

4.1.1. Soil Texture

The results of various soil physical properties evaluated under different LULC types at lower, middle and upper slope positions are presented in Table 3 and 4. Sand particle (62.26%) was the dominant in the particle size distribution of the soil followed by clay (28.44%) with a relatively small portion of silt (9.15%) in the study area. The overall soil textural class was predominantly sandy clay loam, except the soil at lower slope position of the grazing LC type, which exhibited a sandy clay textural class. The analysis of variance indicated that soil particle size distribution was significantly influenced by LULC types and slope positions (Appendix Table 2). Sand and clay contents varied significantly (P<0.001) among LULC types across slope positions suggesting that these factors play the crucial roles in shaping soil particle size distribution. Conversely, the silt content showed non-significant variation among LULC types. However, it demonstrated a highly significant variation (P<0.001) across slope positions, emphasizing the impact of topography on this soil fraction (Appendix Table 2).

Sand content of soil under all LULC types along slope position ranged from 51 to 72%, which was very high according to the ratings of Hazelton and Murphy (2007) (Appendix Table 3). The highest sand content (72%) was recorded for the soil under Khat LU type at the upper slope position and the lowest (51%) was for the soil of grazing LC type at the lower slope. The higher sand content in soil of Khat LU type at the upper slope could be attributed to frequent tillage which can lead to soil erosion, washing of the finer particles like clay and leaving a higher proportion of sand at the upper slope position. In contrast, the soils under grazing LC type at lower slope experiences less disturbance allowing finer particles to remain at place. Furthermore, vegetation cover of grazing LC type protects the soil from erosion and aids in retaining finer particles. In agreement with this, Molla *et.al* (2022) revealed that grazing lands exhibit relatively lower sand content because of grass cover reduces soil erosion and washing of fine particles. Similarly, Kinnelli (2000) reported that higher sand content in soil of steeper slopes, particularly at upper slope position where runoff is more intense associated with higher sediment concentrations due to intensified erosion processes. These effects are exacerbated in Khat LU type at upper slope due to frequent plowing and inadequate replenishment of nutrients through the application of organic matter, which further accelerates soil degradation and erosion. The strong negative correlation (r=-0.987) between sand and clay contents, as shown in Table 9 indicates that a removal of clay content is directly associated with a proportional increase in the sand fraction.

Silt content ranged from 6.33 to 10.33%, which was rated as very low to low. These lower and upper limits of the silt content of soil under all LULC types were recorded for soil of Khat LU type at lower and upper slope positions, respectively. This variation in silt content could be attributed to the accumulation of fine particles at lower slopes as a result of sedimentation processes that are common in undulating landscapes. Amare *et al.* (2024) revealed that soils at lower slopes typically have higher clay and silt content, which enhances soil fertility and moisture retention. Soils of upper slopes have elevated bulk density and diminished nutrient levels, due to erosion and reduced soil quality.

Clay content ranged from 21.33 to 40.33%, rated as low to moderate. Relatively, highest clay content (40.33%) was recorded for the soil of grazing LC type at lower slope position which could be attributed to improved soil structure, minimal disturbance and higher organic matter content (Table 5). The grazing LC type plays a vital role in minimizing erosion and fostering accumulation of organic matter which in turn improves water retention and enhances aggregate stability, leading to better soil quality. Bayle *et al.* (2023) and Bezabih (2014) noted that grazing LC type tends to have significantly higher clay content due to the beneficial effects of the vegetation cover. In contrast, the cultivated LU type on the upper slope showed the lowest clay content (21.33%), which could be attributed to disrupted soil structure and low levels of organic matter (Table 5). Furthermore, agricultural practices and erosion can result in the loss of finer soil particles. Bayle *et al.* (2023) and Bezabih (2014) reported that cultivated LULC type, particularly at upper slopes often experience soil degradation which leads to lower clay content and reduced soil quality. This situation illustrates the effects of LULC types and slope position on soil particle size distribution.

The correlation analysis (Table 9) revealed a strong positive correlation (r=0.929) between clay content and CEC. This result evidenced that an increase of clay content is directly associated with an increase in CEC in study area.

Table 3: The interaction effect of LULC types and slope positions on the physical soil properties in Maya-Guddoo subwatershed

LULC types	Slope Positions	Particle size distribution (%)			STC	ρ_b (g/cm^3)	TP (%)
		Sand	Silt	Clay			
Cultivated	Upper	70.00^{a}	8.67^{bc}	21.33^{f}	SCL	1.31^{c}	50.65^{c}
	Middle	57.33^{d}	9.33^{ab}	33.33^{b}	SCL	1.27^{d}	51.91^{b}
	Lower	64.67^{b}	8.33^{bc}	27.00^{d}	SCL	1.38^{b}	47.87^{d}
Khat	Upper	72.00^{a}	6.33^{d}	21.67^{f}	SCL	1.44^{a}	45.71^{e}
	Middle	56.33^{d}	9.33^{ab}	34.33^{b}	SCL	1.11^{e}	57.94^{a}
	Lower	65.67^{b}	10.33^{a}	24.00^{e}	SCL	1.34^{c}	49.59^{c}
Grazing	Upper	66.00^{b}	7.67^{cd}	26.33^{d}	SCL	1.43^{a}	45.88^{e}
	Middle	61.00^{c}	9.0^{abc}	30.00^{c}	SCL	1.45^{a}	45.13^{e}
	Lower	51.00^{e}	8.67^{bc}	40.33^{a}	SC	1.14^{e}	57.09^{a}
	CV	3.01	9.97	4.35		1.37	1.36
	MSD	2.26	1.04	1.50		0.02	0.82

CV= Coefficient of variance; MSD= Minimum significant difference; ρ_b = Bulk density; SC = Sandy clay; SCL = Sandy clay loam; STC = Soil texture class, TP = Total porosity; Means within row and column followed by the same letter are not significantly different from each other at P ≤ 0.05 according to Tukey's MSD.

4.1.2. Bulk Density and Total Porosity

Soil bulk density affects various soil properties and serves as a key indicator of soil quality and frequently used in different predictive models to evaluate soil quality (Fernandez *et al.*, 2019; Lema *et al.*, 2019). The analysis of variance indicated significant differences (P<0.001) in bulk density and total porosity among the different LULC types across slope positions (Appendix Table 2). Bulk density value ranged from 1.11 to 1.45 g/cm^3, which was rated as low to moderate (Appendix Table 3). The highest bulk density was recorded in grazing LC type (1.45g/cm^3) at the middle slope (Table 3). This could be linked to soil compaction caused by livestock trampling and overgrazing that reduce the pore spaces. Nonexistence of vegetative cover in overgrazed areas exacerbates this process by reducing soil structure stability and promoting crust formation. Supporting this observation, Bezabih (2014) reported that grazing lands often exhibit higher compaction due to livestock trampling which leads to reduced soil porosity. Conversely, the lowest bulk density was recorded in Khat LU type (1.11 g/cm^3) at the same slope which may be a result of minimal disturbance and improved organic matter management that enhances soil structure and aggregate stability. Management practices such as addition of organic matter in this area improve soil structure, increase porosity and reduce bulk density (Table 3). Additionally, cultivation of Khat typically involves minimal tillage practices which contributing to lower bulk density (Bezabih, 2014). The correlation analysis (Table 9) revealed that bulk density had a strong negative correlation (r=-0.999) with total porosity. These results show how compaction due to overgrazing degrades soil and affects sustainable land management to preserve soil health. Rotational grazing or lowering livestock pressure can greatly improve soil conditions in grazing lands by addressing soil compaction.

The total porosity values of the soils in the study area ranged from 44.15 to 58.49% with a mean of 50.20% (Table 3). The highest porosity (57.94%) was recorded for the soil of Khat LU type at the middle slope position which reflects improved soil aggregation from high organic matter input that increases pore space. Furthermore, addition of organic matter and fertility management practices which promote soil aggregation could be the cause of the enhanced porosity of Khat LU type at middle slope. Conversely, lowest porosity (45.13%) of soil under the grazing LC type at the same slope position indicates soil compaction with a reduced number of large pores as a result of low organic matter input and trampling. According to Li *et al.* (2008), livestock trampling on grazing LC type causes soil compaction, which lowers porosity and modifies other physical soil properties.

4.1.3. Soil Water Retention Characteristics

The amount of moisture present in the soil influences how effectively nutrients are absorbed (Yennawar *et al.*, 2013). According to the ANOVA results, soil water content at the field capacity (FC) and permanent wilting point (PWP) showed highly significant differences (P<0.001) in all LULC types across slope positions (Appendix Table 2). In the study area, soil water content at the FC varies from 20.95 to 38.00%. This highest and lowest values of soil water content at the FC was recorded for the soil under the grazing (at the lower slope) and Khat (at the upper slope) LULC types, respectively. The highest soil water content at the FC could be attributed to higher clay content (Table 3) and organic matter accumulation (Table 5), both of which enhances water retention. By preventing erosion and encouraging the accumulation of organic matter the grazing LC type frequently preserves a protective cover that improves the capacity of soil to retain moisture. On the other hand, the lower water content at the FC in Khat LU type at upper slope position could result from the lower organic matter content and a high sand content which tends to drain water more quickly and does not retain moisture effectively. In line with this, Fantaw *et al.* (2008) revealed that grazing LC type can maintain higher levels of organic matter compared to cultivated LU type which lead to better soil structure and moisture retention. Intensive cultivation as seen in Khat LU type can lead to nutrient depletion and washed away the finer particles which may further exacerbate the challenges of soil water retention (Eyasu, 2017). In contrast, the natural vegetation of grazing LC type can contribute to the organic matter and aids to protect the soil from erosion and evaporation which in turn supports improved soil structure and nutrient levels, thereby enhancing water retention capability.

The highest (21.12%) soil water content at the PWP was recorded for the soil under Khat LU type at middle slope position and the lowest (8.81%) was recorded for the same LU type at lower slope position (Table 4). This observation highlights the significant impact of LULC types and slope positions on soil moisture retention. The highest mean of soil water content at the PWP indicates that higher retention of water which is not available to plants, which may be attributed to higher clay content (Table 3) which enhances moisture retention due to its fine texture and extensive micro pore space. Even at the wilting point, higher residual moisture is maintained in clay-rich soils due to the greater total porosity, which holds water more tightly and prevents drainage and plant uptake. Fine-textured soils, such as clays have higher moisture content at PWP due to their ability to hold water in micro-pores under high tension. In contrast, coarse-textured soils like sands have lower moisture content at PWP because their larger pores cannot retain water as effectively against gravitational forces (O'Geen, 2013). According to Bayle *et al.* (2023), the higher organic matter and improved soil structure leading to increased water retention capacity and resulting in a higher moisture content at PWP. Conversely, the lower soil water content at the PWP indicates the reduced water retention due to a predominance of sandy texture and soil structure disturbances that facilitate the loss of water from soil. In line with this conclusion, Hansong *et al.* (2022) found that the intensive farming often leads to diminishes organic matter levels through the removal of crop residues and the disturbance of soil structure. When soil compaction occurs and organic matter is reduced, the ability of soil to retain water at levels above the soil water content at the PWP decreases (Hansong *et al.*, 2022). Overall, the differences in soil water content at the PWP due to variations in soil texture, organic matter and slope-induced erosion affect the ability of soil to retain water at levels that are unavailable for plant uptake.

Available water holding capacity (AWHC) of the soil showed non-significant differences among LULC types, but there were highly significant variations in relation to slope positions (Appendix

Table 2). The maximum AWHC was calculated for grazing LC type at the lower slope position (17.54%), which belongs to the medium category according to Beernaert and Bitondo (1990) rating. The minimum AWHC was calculated for the same LC type at the upper slope position (10.58%), which was rated as low by the same classification. Higher AWHC of soil under the grazing LC type at lower slope position is likely attributed to its higher clay content and water content at field capacity (Table 3 and 4). Clay particles have a larger surface area, abundant micro pores, which tightly retain water through strong adhesive and cohesive forces and can retain more water compared to sand or silt which results in increased water retention within the soil. According to Zhang and Song (2023), the clay particles have a high surface area that facilitates water adsorption through van der Waals forces and hydroxyl hydration, significantly enhancing water retention at the Nano scale. The soils at lower slopes tend to accumulate more organic matter and finer particles, which contribute to enhanced water retention and availability for plant use. The Nano scale structure of clay particle allows for effective capillary action that becomes more prominent as the water content increases further contributing to its water retention capabilities. In contrast, the grazing LC type at the upper slope showed the lowest AWHC. Typically, the soils at the upper slope have coarser textures, lower clay content and reduced organic matter (Bayle *et al.*, 2023; Bezabih, 2014), primarily due to erosion and runoff. These conditions limit the capacity of soils to retain water as larger soil particles like sand, allow water to drain more quickly. Additionally, the lower water content at the field capacity at upper slope position leads to less water available for plants between rainfall events, further diminishing AWHC in this area.

Moisture content showed a significant variation under different LULC types across slope positions (Appendix Table 2). Moisture content of soils in study area ranged from 9.80 to 28.57%. The highest value of moisture content (28.57%) was recorded under the soil of Khat LU type at the middle slope position possibly due to the contributions of organic matter and the shading effects of dominant Khat crop in this area, which reduced the surface evaporation due to dense canopy cover. In line with these observations, Xuemei *et al.* (2018) revealed that Khat LU type characterized by dense vegetation enhances moisture retention by minimizing evaporation and enhancing infiltration. Conversely, the lowest moisture content (9.80%) was recorded for the same LU type at lower slope position; this could be due to a combination of soil compaction and lower clay content (Table 3). According to Ramesh *et al.* (2024), the soil compaction decreases porosity and moisture retention. Contrary, the findings indicate that the lower slopes generally receive more water from runoff from upper slopes, while upper slopes experience higher evaporation rates (Xuemei *et al.*, 2018) owing to less vegetation and higher exposure to the sun, resulting in lower moisture content in these areas. This finding considered only the slope, but in the current study, the lowest moisture content was observed in the Khat LU type at lower slope position, likely due to the reduced water retention capacity (Table 4), low clay content (Table 3) and intensive land management practices associated with Khat cultivation in this area.

Table 4: The interaction effect of LULC types and slope positions on the gravimetric soil water content at FC, PWP, AWHC and MC in the study area

LULC types	Slope Position	FC (%)	PWP (%)	AWHC (%)	MC (%)
Cultivated	Upper	23.37^{d}	10.90^{c}	12.47^{cd}	16.50^{c}
	Middle	27.86^{c}	12.88^{b}	14.98^{b}	12.67^{d}
	Lower	22.85^{de}	9.82^{cd}	13.03^{bc}	12.90^{d}
Khat	Upper	20.95^{e}	10.25^{cd}	10.70^{d}	18.33^{b}
	Middle	35.78^{b}	21.12^{a}	14.66^{b}	28.57^{a}
	Lower	21.26^{e}	8.81^{d}	12.45^{cd}	9.80^{e}
Grazing	Upper	23.49^{d}	12.91^{b}	10.58^{d}	16.53^{c}
	Middle	22.11^{de}	9.52^{cd}	12.59^{cd}	12.50^{d}
	Lower	38.00^{a}	20.47^{a}	17.54^{a}	27.80^{a}
	CV	4.29	7.16	8.95	3.55
	MSD	1.35	1.12	1.42	0.74

AWHC = Available water holding capacity; FC = Field capacity; MC = Moisture content; PWP = Permanent wilting point; Means within row and column followed by the same letter are not significantly different from each other at $P \leq 0.05$ according to Tukey's MSD.

4.2. Effects of LULC types and Slope Positions on Chemical Properties of Soil

4.2.1. Soil Reaction

Soil pH is considered as an important soil property that determines the nutrient solubility and the physical condition of the soil, which in turn regulates the diversity of microbes present in the soil (Abraham *et al.*, 2019). The analysis of variance for pH showed that both LULC types and slope positions significantly ($P<0.001$) affected the soil pH in the study area (Appendix Table 8). The highest pH (7.85) was recorded for soil of Khat LU type at the middle slope position (Table 5), which was rated as moderately alkaline according to Foth and Ellis (1997) ratings; suggesting reduced leaching of bases relative to other LULC types (Table 6) and the deposition dissolved nutrients and basic cations from the upper slopes play a role in neutralizing soil acidity. Furthermore, the addition of organic matter could raise the soil pH by lowering soil acidification processes at this slope position. Conversely, Khat LU type at upper slope position exhibited the lowest pH (7.06), rated as neutral according to the same author. This may be attributed to higher leaching of basic cations. Generally, higher soil pH value for soil of Khat LU type at middle slope position could be attributed to the accumulation of basic cations through runoff and deposition from the upper slope positions. Previous reports indicate that slope and management practices influence soil chemical properties by modifying erosion, leaching and organic matter content (Bayle *et al.*, 2023; Zhang *et al.*, 2017).

Among the LULC types in the study area, the highest pH value was recorded for the soil of cultivated LU type (7.51), followed by grazing LC type (7.43) and the lowest value for Khat LU type (7.41). This indicates that cultivation practices involve fertilizers or nutrient management that raises soil pH. These findings align with those of Mengiste *et al.* (2015), who reported a regular application of lime and fertilizers raises soil pH and enhance nutrient availability. Such practices are beneficial for creating a more conducive environment for nutrient uptake by plants and improving overall soil fertility and quality.

4.2.2. Electrical Conductivity

According to the analysis of variance for soil Electrical Conductivity (EC), values varied significantly ($P<0.001$) across LULC types and slope positions (Appendix Table 8). The highest EC (0.26 dS/m) was recorded for the soil at lower slope of grazing LC type. This could be attributed to the accumulation of salts from runoff and reduced leaching at this slope position, leading to the higher concentration of soluble ions, potentially influenced by increased nutrient levels and moisture contents (Table 4), thereby collectively contribute to the higher EC value. In agreement with this finding, Eshetu and Lemma (2024) revealed that the EC value is influenced by the concentration of dissolved salts and nutrients in the soil solution; with higher nutrients and moisture content leading to higher EC value. According to Ayalew *et al.* (2023), grazing LC type, particularly those at the lower slopes often have higher EC value due to the accumulation of animal waste and organic matter, which decompose and release soluble ions (e.g., nitrates, potassium and sodium) into the soil, thereby increases the availability of soluble ions. Contrary to this finding, Mengiste *et al.* (2015) found that grazing LC type generally have higher organic matter content, which can enhance the leaching of soluble salts resulting in lower EC values. However, in this study, the higher EC value seen in the grazing land at the lower slope was due to the interaction between LULC types and slope positions. Furthermore, lower slope positions act as depositional zones where water and nutrients accumulate due to surface runoff from upper slope positions. This retained moisture enhances the dissolution of salts and ions, raising the soil EC. In contrast, the lowest EC (0.03 dS/m) was observed at upper slope positions of both cultivated and Khat LU types, which can be attributed to higher water drainage and continuous leaching driven by higher infiltration rates and steep gradients. These conditions result in a lower silt and clay content due to erosion, as observed in both LU types at upper slope positions (Table 2), which in turn reduces the retention of soluble salts. Furthermore, the intensive cultivation practices exacerbate the depletion of nutrients and soluble salts from the soil. Supporting this finding, Eshetu and Lemma (2024) found that cultivated lands, particularly at the upper slope often exhibit lower EC values due to intensive farming practices that cause the loss of vital soil nutrients and organic matter.

4.2.3. Soil Organic Matter Content

The analysis of variance indicated that organic matter (OM) levels varied significantly ($P<0.001$) among LULC types across slope positions (Appendix Table 8). Grazing LC type exhibited the highest OM content (3.19%), while cultivated LU type had the lowest (2.30%) organic matter content. This difference could be attributed to fewer disturbances in case of grazing LC type, which allow for higher accumulation of organic matter. Across the slope positions, the highest OM (3.43%) was recorded for soil at lower slope positions, probably due to the deposition of organic-rich materials, while the lowest OM (2.53%) was recorded for soil at middle slope positions.

The organic matter values in the soil of study area ranged from 1.95 to 4.91%, which belongs in low to medium categories according to Berhanu (1980) ratings. The highest SOM (4.91%) was recorded for the grazing LC type at lower slope position, indicating better soil conditions due to less disturbance and higher organic input from vegetation cover. In contrast, the lowest SOM (1.95%) was recorded for cultivated LU type at lower slope position, probably due to soil disruption and organic matter depletion resulting from intensive tillage practices (Eshetu and Lemma, 2024). According to Shiferaw *et al.* (2019), the grazing LC type at the lower slopes demonstrated significantly higher soil organic carbon (SOC) levels compared to cultivated LU type, suggesting that minimal disturbance and sustained organic inputs; however the cultivation practices tend to reduce the SOC through tillage, crop removal and erosion. Typically, cultivated LU types exhibit lower SOM as a result of agricultural practices like tillage; which disrupt soil structure and diminishes organic inputs subsequently lowering soil organic matter levels (Göl and Yilmaz, 2017). This reduction in SOM content has significant implications for soil fertility, quality and overall ecosystem health. The effects of different LULC types and slope positions plays a pivotal role in determining the distribution of the SOM content, thereby affecting the soil fertility and quality across the landscape.

4.2.4. Total Nitrogen and Carbon to Nitrogen Ratio

The total nitrogen (TN) content of soil indicated significant variations across different LULC types ($P<0.05$), but the impact of slope positions was non-significant. Nevertheless, the interaction between these factors showed a highly significant effect ($P<0.001$) (Appendix Table 8). The grazing LC type recorded the highest TN (0.19%) compared to Khat (0.16%) and cultivated LU types (0.16%). These differences are likely related to organic matter inputs and nitrogen-fixing vegetation cover in grazing areas that boost TN levels. Slope position did not show significant effects independently.

Total Nitrogen (TN) values in soil of the study area ranged from 0.09 to 0.24%, which was rated as low to medium range according to Havlin (1999) ratings. The highest TN content (0.24%) was recorded in soil of grazing LC type at lower slope position, likely due to the accumulation of organic matter and less soil disturbance. Grazing LC types maintain natural vegetation cover which helps in nitrogen cycling and lowers nutrient losses. Conversely, the Khat LU type at lower slope exhibited the lowest TN (0.09%), possibly due to nitrogen depletion resulting from frequent Khat harvesting without adequate replenishment and decreased nitrogen fixation. This observation aligns with Kepp *et al.* (2024), who reported that grazing LC type enhances topsoil nitrogen stocks by promoting organic matter accumulation and reducing soil disturbance, while Khat LU type experiences nitrogen depletion from frequent harvesting and inadequate organic matter contributions. Overgrazing and frequent harvesting lead to nitrogen depletion and a decline in soil fertility, whereas moderate grazing increases the total nitrogen (TN) of the soil through the accumulation of organic matter (Wang *et al.*, 2023). Overall, the grazing LC type promotes more favorable nitrogen dynamics that support biological nitrogen fixation enhancing soil nitrogen levels (Wang *et al.*, 2023).

According to the analysis of variance the LULC types and slope positions impacted the C:N ratio significantly (Appendix Table 2). Among the LULC types, Khat exhibited the highest C:N ratio

(13.12), indicating the presence of more resistant organic material, which is slow to decomposition (lignin-rich leaves) and lower nitrogen inputs. In contrast, the lower C:N ratio (8.64) calculated for the soil of cultivated LU type indicates faster organic matter decomposition and nutrient cycling. The highest C:N ratio (13.97) was recorded at the lower slope position, likely due to the accumulation organic material transported from the upper slopes. In contrast, the lowest C:N ratio (8.21) was recorded at the middle slope position, suggesting a more active decomposition process.

The soil under Khat LU type at the lower slope position had the highest C:N ratio (22.30), which indicated a slower rate of organic matter decomposition and higher organic matter input. In contrast, the cultivated LU type displayed the lowest ratios (between 7.49 and 10.16) across all slope positions (Table 5), indicating a high rate of nutrient turnover attributed to frequent disturbances. As stated by Ghimire *et al.* (2023), the cultivated LU type had lower C:N ratio compared to natural forest and grazing LC type , due to its frequent subjection to intensive management and nutrient depletion, which results in lower C:N ratios. The C:N value of grazing LC type at lower slope showed the highest ratio (12.13), implying that the input of organic matter and its decomposition were relatively balanced. Furthermore, the reduced decomposition rates and low nitrogen inputs contribute to the high C:N ratio. These trends demonstrate how slope position and land management practices affect the dynamics of soil carbon and nitrogen.

4.2.5. Available Phosphorus

The analysis of variance for available phosphorus (AV.P) in soil of study area across LULC types and slope positions indicates highly significant differences (P<0.001). Soil of Khat LU type recorded the highest value (18.52 mg/kg), followed by that of cultivated (6.95 mg/kg) and grazing (6.59 mg/kg) LULC types. In terms of slope positions, soil at lower slope position exhibited highest AV.P level (12.95 mg/kg), followed by the middle slope (11.73 mg/kg). The lowest value (7.38 mg/kg) of AV.P was recorded for soil at upper slope position. The significant variations in soil available phosphorus (AV.P) levels emphasize the influence of organic inputs and slope on nutrient retention and distribution. Contrary to this finding, Sigua *et al.* (2011) reported that the phosphorus accumulation is highest at the top slope and decreases significantly as one moves towards the bottom slope, with a 40% reduction noted in herbage mass and phosphorus accumulation from top to bottom. This observation is attributed to the absence of visible erosion effects and the study was limited to pastureland. However in current study the variation in AV.P levels due to the effects of slope positions, LULC types and associated management practices.

The AV.P values fell into very low to high categories as per Olsen *et al.* (1954) ratings of AV.P, ranging from 2.46 to 23.41 mg/kg. In combined analysis, the Khat LU type exhibited the highest AV.P levels (23.41 mg/kg) at lower slope position (Table 4). This is probably due to a greater presence of organic inputs and the addition of inorganic fertilizers. On the other hand, grazing LC type showed the lowest AV.P level (2.46 mg/kg) at the upper slope. This could be due to fewer external inputs like fertilizers; with phosphorus potentially being fixed by clay minerals or immobilized in organic complexes particularly in soils with high CEC and clay content. Cayley *et al.* (2022) described that grazing lands often exhibit reduced phosphorus levels due to nutrient depletion from livestock grazing, while high grazing pressure may initially raises P levels, ultimately leading to depletion over time.

4.2.6. Cation Exchange Capacity

The analysis of variance for Cation Exchange Capacity (CEC) showed significant variations ($P<0.001$) across various LULC types and slope positions (Appendix Table 8). The CEC of the soil under grazing LC type had the highest value (35.84 cmol(c)/kg), whereas the soil under Khat (29.30 cmol(c)/kg) and cultivated (30.22 cmol(c)/kg) LU types showed no significant differences and exhibited similar results. The influence of slope position was evident, exhibiting significantly lower soil CEC at upper slope positions (24.98 cmol(c)/kg) when compared to that of at middle (35.28 cmol(c)/kg) and lower slopes (35.12 cmol(c)/kg).

The CEC values in the soil of study area ranged from 21.53 to 47.37 cmol(c)/kg, indicating medium to very high levels according to per Landon (1991) CEC ratings. The highest (47.37 cmol(c)/kg) CEC value was recorded for soil of grazing LC type at lower slope position, which could be attributed to better organic matter, high clay content and fewer disturbances compared to other LULC types. The CEC values for the soil of Khat and cultivated LU types at middle slopes were high (34.97 cmol(c)/kg and 38.33 cmol(c)/kg, respectively), followed by that of grazing LC type at the lower slope position, probably due to the accumulation of organic material and finer soil particles from the upper slopes. According to Eshetu *et al.* (2024), middle slope areas can benefit from effective soil management practices like cover cropping and organic amendments in these LU types, which can improve soil structure and increase organic matter content; ultimately leading to higher CEC and improved soil fertility and quality. In contrast, the lowest CEC value (21.53 cmol(c)/kg) was recorded for soil of Khat LU type at upper slope position, indicating limited accumulation of organic matter and clay due to runoff effects on steeper terrain. Additionally, Eshetu *et al.* (2024) reported lower CEC values for cultivated lands at steeper slopes, likely due to erosion. This study revealed that CEC values of the soil under grazing LC types at the lower slope positions and the soil of Khat and cultivated LU types at the middle slope positions were higher, indicating better soil properties that enhance nutrient retention and availability (Ayalew *et al.*, 2023). while the soil of all LULC types at upper slope positions exhibited lower values, primarily because of relatively higher sand content, and lower clay and organic matter contents in the soil at these areas (Table 3 and 5). The combined influence of LULC types and slope positions suggest that both soil management and terrain features influence the nutrient retention and soil fertility and quality.

Table 5: The interaction effect of LULC types and slope positions on chemical soil properties in Maya-Guddoo subwatershed

LULC Types	Slope Position	pH (H_2O)	EC (dS/m)	CEC (cmol(c)/kg)	AV.P (mg/kg)	OC (%)	OM (%)	TN (%)	C:N
Cultivated	Upper	7.39^{e}	0.03^{e}	25.77^{e}	4.27^{ef}	1.48^{e}	2.55^{e}	0.15^{d}	10.16^{bc}
	Middle	7.37^{f}	0.05^{c}	38.33^{b}	5.06^{e}	1.39^{g}	2.40^{f}	0.17^{cd}	8.27^{cd}
	Lower	7.76^{b}	0.06^{b}	26.57^{e}	11.52^{d}	1.13^{h}	1.95^{g}	0.15^{cd}	7.49^{d}
Khat	Upper	7.06^{h}	0.03^{e}	21.53^{f}	15.40^{bc}	1.93^{c}	3.32^{c}	0.21^{ab}	9.08^{cd}
	Middle	7.85^{a}	0.06^{b}	34.97^{c}	16.75^{b}	1.44^{f}	2.49^{e}	0.18^{bc}	7.96^{d}
	Lower	7.33^{g}	0.04^{de}	31.41^{d}	23.41^{a}	1.99^{b}	3.43^{b}	0.09^{e}	22.30^{a}
Grazing	Upper	7.43^{d}	0.043^{d}	27.63^{e}	2.46^{f}	1.13^{h}	1.96^{g}	0.14^{d}	7.98^{d}
	Middle	7.34^{g}	0.06^{b}	32.53^{cd}	13.37^{cd}	1.56^{d}	2.69^{d}	0.19^{bc}	8.40^{cd}
	Lower	7.53^{c}	0.26^{a}	47.37^{a}	3.93^{ef}	2.85^{a}	4.91^{a}	0.24^{a}	12.13^{b}
	CV	0.21	4.34	5.39	12.16	2.78	1.30	11.71	11.83
	MSD	0.02	0.004	2.06	1.56	0.03	0.04	0.02	1.48

AV.P=Available phosphorus; CEC=Cation exchange capacity; C:N=Carbon to Nitrogen ratio; EC=Electrical conductivity; OC=Organic carbon; OM=Organic matter; pH=Soil reaction; TN=Total Nitrogen; Means within row and column followed by the same letter are not significantly different from each other at $P \leq 0.05$ according to Tukey's MSD.

4.2.7. Exchangeable Bases and Percent Base Saturation

All exchangeable bases (K^+, Mg^{+2}, Na^+ and Ca^{+2}) showed significant variations ($P<0.001$) across different LULC types and slope positions; however the PBS did not show significant differences (Appendix Table 9). The highest levels of Na (1.70 cmol(c)/kg) and Mg (30.87 cmol(c)/kg) were recorded for soil of grazing LC type at lower slope position. The highest Ca (17.77 cmol(c)/kg) and K (1.43 cmol(c)/kg) contents were recorded for soil of Khat LU type at the middle slope position, while the lowest K (0.66 cmol(c)/kg) levels were recorded for soil of cultivated LU type at the upper slope position. Additionally, the lowest Na (0.60 cmol(c)/kg), Ca (6.31 cmol(c)/kg) and Mg (11.84 cmol(c)/kg) were recorded for soil of Khat LU type at upper slope positions (Table 6).

The sodium (Na) content in the soil of study area ranged from 0.60-1.70 cmol(c)/kg, with medium to high levels in soil of cultivated and Khat LU types and high to very high levels in soil of grazing LC type according to FAO (2006) ratings. The increased levels of sodium (Na) in the soil of grazing LC type at lower slope position was likely attributed to runoff and the natural accumulation of salts downslope combined with limited leaching. Consistent with this finding, Bayle *et al.* (2023) found that the grazing LC type generally showed greater nutrient concentrations due to contributions from livestock and decomposing plant material. The same authors also noted that areas at the lower slopes benefit from runoff, which promotes the accumulation of sodium (Na) content. In contrast, lower Na levels in soil of Khat LU type at the upper slope may be attributed to a number of factors, such as the limited retention capacity due to high sand content and enhanced leaching and the well-drained conditions typical of upper slope positions. Furthermore, the loss of fine particles and associated cations due to soil erosion processes at the upper slope position may further reduce Na levels.

According to FAO (2006) ratings, potassium (K) was rated as high to very high (0.66 to 1.43 cmol(c)/kg) in the study area. The highest Potassium (K) levels in soil of Khat LU type at middle slope might be due to the recycling of nutrients from leaf litter, optimal conditions for retaining nutrients and the effects of organic inputs, as farmers in study area prioritize soil fertility management in Khat cultivation. Conversely, lower Potassium (K) levels in soil of cultivated LU type at upper slope position could be attributed to ongoing crop harvesting which leads to the depletion of Potassium along with possible erosion at upper slope positions. Literature shows that intensive farming methods across various types of land use have a considerable impact on potassium levels (Akbal *et al.*, 2017). According to Sharma *et al.* (2006), the levels of potassium differ considerably among various landforms with higher amounts generally present in the soils having high finer particles and cation exchange capacity like the Khat LU type at lower and middle slope positions and cultivated LU type at middle slope position (Table 3 and 5). In contrast, the reduced levels noted in the cultivated LU type at upper slope position can be attributed to intensive agricultural practices (Eshetu and Lemma, 2024).

The Ca^{+2} content in soil of Khat LU type at the middle slope position (17.77 cmol(c)/kg) was high, while Khat LU type at upper slope (6.31 cmol(c)/kg) was medium (FAO,2006). The highest calcium content in soil of Khat LU type at middle slope might be resulted from the runoff higher elevation carries sediment-bound and dissolved calcium (Ca) from the higher to the middle and lower elevations, where it builds up. In the meantime, stored calcium is released into the soil by decomposing organic matter, increasing its availability even more. Higher soil Ca content results from Ca persisting and building up in these nutrient-rich zones because it is less prone to leaching than more mobile nutrients (like nitrates). In addition, the Khat domination at middle slope may be less prone to erosion compared to steeper slope in study area. In agreement with these findings, Lal (2001) revealed that middle slopes are typically less prone to erosion compared to upper slopes, resulting in better retention of top soil and related nutrients including Ca content. Effective nutrient cycling and decreased nutrient loss may be facilitated by the particular microclimate and vegetation cover connected to Khat cultivation (Asefa *et al.*, 2010). Conversely, the lower calcium (Ca^{+2}) levels observed in the Khat LU type at the upper slope could be due to erosion and nutrient leaching in these areas. In consistence with this Brady and Weil (2008) explained that continuous cultivation can deplete soil nutrients through crop removal and accelerated mineralization rates.

The Magnesium (Mg) contents in soil at all slope positions ranged from high to very high according to FAO (2006) ratings. The highest Magnesium (Mg^{+2}) level (30.87cmol(c)/kg) was recorded for soil of grazing LC types at the lower slopes, probably due to magnesium accumulation at this slope position from runoff, clay's strong magnesium retention, limited leaching and enhanced organic matter which can improve magnesium retention. In alignment with this, Lal (2001) revealed that lower slopes frequently receive the sediment deposition from higher slopes which can enrich the soil with nutrients including Magnesium. Grazing LC types usually have lower nutrient demands than cultivated, leading to greater nutrient retention in the soil (Brady and Weil, 2008). In contrast, soil at upper slopes under Khat cultivation might suffer from magnesium depletion due to erosion and reduced organic matter contributions, restricting magnesium concentrations in the soil. Also, the rapid erosion causes the washing away of nutrients at steep slopes (Lal, 2001).

The ANOVA result revealed that no statistically significant differences for the PBS values. However, the values varied numerically amongst LULC types and slope positions. For instance, compared to grazing LC types, soils under Khat LU at the upper slope tended to exhibit relatively lower PBS. This could be partially attributed to factors like erosion on steeper slopes (Lal, 2001), which could result in losses of topsoil and basic cations. Reduced base saturation over time may also result from the use of chemical fertilizers and minimal organic matter input from crop residues (Brady & Weil, 2008). On the other hand, because of less disturbance and more stable nutrient retention, grazing LC types at lower slope position showed numerically higher PBS values. Grazing systems generally impose lower nutrient extraction pressures than cultivated lands (Brady & Weil, 2008), and lower slopes frequently benefit from sediment deposition (Lal, 2001).

Table 6: The interaction effect of LULC types and slope positions on basic exchangeable cations and PBS in Maya-Guddoo subwatershed

LULC Types	Slope Positions	Exchangeable Basic Cations (cmol(c)/kg)				PBS (%)
		Na	K	Ca	Mg	
Cultivated	Upper	0.76^{cd}	0.66^{f}	7.90^{f}	14.97^{d}	94.83^{ab}
	Middle	0.85^{bc}	1.16^{c}	11.99^{d}	23.73^{b}	98.12^{ab}
	Lower	0.62^{d}	0.70^{f}	9.61^{e}	15.34^{d}	98.69^{ab}
Khat	Upper	0.60^{d}	0.90^{e}	6.31^{g}	11.84^{e}	91.53^{b}
	Middle	0.82^{c}	1.43^{a}	17.77^{a}	14.58^{d}	98.88^{a}
	Lower	0.68^{cd}	1.04^{cd}	14.78^{b}	14.02^{d}	97.07^{ab}
Grazing	Upper	1.02^{b}	1.00^{de}	7.86^{f}	17.08^{c}	97.69^{ab}
	Middle	1.02^{b}	0.97^{de}	11.20^{d}	18.39^{c}	97.15^{ab}
	Lower	1.70^{a}	1.30^{b}	13.82^{c}	30.87^{a}	100^{a}
	CV	11.22	6.99	4.20	5.38	4.35
	MSD	0.12	0.09	0.57	1.16	5.09

Ca=Calcium; K=Potassium; Mg=Magnesium; Na=Sodium; PBS=Percent Base Saturation; Means within row and column followed by the same letter are not significantly different from each other at $P \leq 0.05$ according to Tukey's MSD.

4.2.8. Extractable Micronutrients

All micronutrients varied significantly among LULC types across slope positions (Appendix Table 10). The grazing LC type exhibits the highest Fe (26.04mg/kg) and Cu (6.45mg/kg) concentrations at the lower slope. The enrichment of Fe and Cu can be linked with the high clay content, sediment deposition, waterlogging-induced redox reaction, organic matter chelation and reduced leaching in this area, which improve the ability of soil to retain nutrients. Under these conditions, micronutrients such as Fe and Cu are less susceptible to leaching and can build up over time. According to prior studies (Pimentel, 1995; Brady and Weil, 2008; Lal, 2001) the sediment deposition, organic matter input and lower nutrient extraction in this region lead to the highest Fe and Cu contents. In contrast, the lowest Fe (8.18 mg/kg) and Cu (1.00 mg/kg) contents were recorded in the soil under Khat LU type at middle and upper slope positions, respectively. This might be the result of limited organic inputs, leaching processes, erosion effects and the nutrient extraction by Khat crop. Growing Khat can deplete soil nutrients, including Fe and Cu, because of the high nutrient demands of the crop (Tesfaye *et al.*, 2015). According to Jones (2003) ratings, the Fe and Cu content in study area ranged from medium to high and low to high respectively (Appendix Table 7).

The soil under Khat LU type at lower slope position had the highest level of Zn (4.33 mg/kg); and the highest Mn (23.78 mg/kg) was observed in grazing LC type at middle slope; which might have been attributed to the grazing LC type experiencing less soil disturbance and organic matter contributions, which help maintain nutrient stability and enhance the availability of micronutrients over time. Conversely, the lowest content of Zn (1.04 mg/kg) and Mn (12.31 mg/kg) were observed at upper slope positions of cultivated and Khat LU types, respectively. This might be due to intensive tillage and insufficient crop residue which decreases soil organic matter and impacts both its structure and capacity to hold nutrients. On steeper upper slopes, surface runoff leads to erosion that strips away topsoil, further depleting vital nutrients. This continuous disturbance leads to a decline of the CEC of soil, impairing its capacity to retain micronutrients. Micronutrient availability is extremely sensitive to changes in the soil environment (Wajahat *et al.*, 2006). Key determinants of micronutrient content include sand and clay fractions, soil pH and organic matter. According to Araba (2021), additional contributors are cultivation intensity, erosion, leaching, soil drainage characteristics and soil type. These factors most likely explain the differences in micronutrient levels observed across LULC types and slope positions in the study area, in line with the broader knowledge of soil nutrient dynamics and environmental influences. According to Jones (2003) ratings, Zn content ranged from low to medium and Mn levels falling in very high range (Appendix Table 7).

Table 7: Mean values of micronutrients as influenced by LULC types and slope positions

LULC Types	Slope Position	Extractable Micronutrients (mg/kg)			
		Fe	Zn	Cu	Mn
Cultivated	Upper	16.89^{c}	1.04^{e}	1.48^{cde}	13.39^{d}
	Middle	16.07^{cd}	1.87^{c}	1.95^{bc}	16.35^{c}
	Lower	14.95^{cd}	2.72^{b}	1.94^{bcd}	13.15^{d}
Khat	Upper	23.36^{b}	2.66^{b}	1.00^{e}	12.31^{d}
	Middle	8.18^{e}	2.90^{b}	1.30^{e}	14.20^{d}
	Lower	13.84^{d}	4.33^{a}	2.35^{b}	17.51^{c}
Grazing	Upper	16.22^{cd}	1.14^{de}	1.45^{de}	13.55^{d}
	Middle	17.26^{c}	1.65^{cd}	2.25^{b}	23.78^{a}
	Lower	26.04^{a}	3.94^{a}	6.45^{a}	20.92^{b}
	CV	8.83	12.56	12.92	7.19
	MSD	1.80	0.37	0.35	1.40

Cu=Copper; Fe=Iron; Mn=Manganese; Zn=Zinc; Means within row and column followed by the same letter are not significantly different from each other at $P \leq 0.05$ according to Tukey's MSD.

4.3. Effects of LULC types and Slope Positions on Soil Quality

The selected indicators in the minimum data set for this study were sand, silt, clay, bulk density, total porosity, water content at field capacity, AWHC, soil pH, cation exchange capacity, soil organic carbon, total nitrogen, available phosphorus, extractable iron and zinc (Table 2). These indicators have been consistently reported in previous studies (Yared, 2018; Yoseph *et al.*, 2017; Aweke *et al.*, 2015; Gebreyesus, 2014; Rakesh and Kottapalli, 2012; Teklu *et al.*, 2007). According to the analysis of variance both of the LULC types ($P<0.05$) and slope positions ($P<0.001$) significantly impacted the soil quality index (SQI), with each factor making a considerable contribution to the variability observed in soil quality index values (Appendix Table 11).

The soil of Khat and grazing LC types (0.65 and 0.64, respectively) exhibited comparable soil quality index values, whereas the soil under the cultivated LU type had a lower SQI of 0.62, all of which were classified as good soil quality class (Appendix Table 12). Regarding the slope positions, the highest SQI (0.67) was calculated for soil at middle slope position followed by lower slope position (0.65), while the soil at upper slope had the lowest SQI value (0.59).

The soil quality index (SQI) values in study area were rated as moderate to good according to Cantu (2007) ratings (Appendix Table 12). The significant differences in SQI arise from land management practices, levels of soil organic matter input and erosion vulnerability. The results demonstrate that the middle slope of Khat LU type had the highest SQI value (0.73); which could be linked to high organic matter inputs and reduced risk of erosion compared to the steeper upper slopes. Since the soil of Khat LU type is typically less disturbed than cultivated areas, it might retain organic matter more effectively, thereby improving soil structure and nutrient retention capacity. Furthermore, farmers in the study area prioritize cultivating Khat crop due to its high economic value, directing their focus toward management practices in this Khat-dominated area. Practices in Khat cultivation at middle slope position, such as applying fertilizers and weed control, improve the soil nutrient availability and functionality, which are directly reflected in the SQI in the study area.

On the other hand, soil of cultivated and Khat LU type at the upper slope positions showed the lowest SQI value (0.59 and 0.58, respectively), which may be due to intensive tillage practices, low CEC (Table 5) and a lack of crop residues, which restrict the replenishment of organic matter and leave the soil vulnerable to erosion. In grazing LC type, the moderate SQI value observed, especially at lower slope position (0.68) may be due to decreased soil disturbance and the presence of natural vegetation cover. Allowing plant residues to decompose naturally in this area contributes to high organic matter content (Table 5) over time. These organic materials improve soil composition and increase its ability to retain water by maintaining soil porosity. Furthermore, soil at lower slope position in case of grazing LC type is generally less susceptible to erosion, which promotes nutrient retention and accumulation of organic matter, thereby contributing to the sustainable quality of the soil.

Table 8: Interaction effect of LULC types and slope positions on soil quality index in Maya-Guddoo subwatershed and the soil quality classes

LULC Types	Slope Position	SQI	Rating (Cantu, 2007)
Cultivated	Upper	$0.59^{\mathbf{d}}$	Moderate
	Middle	$0.64^{\mathbf{c}}$	Good
	Lower	$0.63^{\mathbf{c}}$	Good
Khat	Upper	$0.58^{\mathbf{d}}$	Moderate
	Middle	$0.73^{\mathbf{a}}$	Good
	Lower	$0.64^{\mathbf{c}}$	Good
Grazing	Upper	$0.60^{\mathbf{d}}$	Good
	Middle	$0.64^{\mathbf{c}}$	Good
	Lower	$0.68^{\mathbf{b}}$	Good
	CV	2.61	
	MSD	0.02	

Table 9: Pearson`s correlation matrix for selected soil properties under different LULC types and slope positions.

	Sand	Silt	Clay	DB	TP	FC	AWHC	pH	CEC	AV.P	OC	TN	Fe	Zn
Sand	1.000													
Silt	-0.469	1.000												
Clay	-0.987	0.325	1.000											
DB	0.739	-0.444	-0.713	1.000										
TP	-0.731	0.444	0.703	-0.999	1.000									
FC	-0.859	0.240	0.877	-0.922	0.918	1.000								
AWHC	0.033	0.106	-0.055	-0.021	0.012	-0.111	1.000							
pH	-0.520	0.372	0.491	-0.589	0.579	0.568	0.453	1.000						
CEC	-0.952	0.510	0.929	-0.724	0.722	0.812	-0.225	0.324	1.000					
AV.P	0.192	0.294	-0.258	0.083	-0.077	-0.249	0.264	-0.038	-0.236	1.000				
OC	-0.392	0.055	0.410	-0.400	0.418	0.455	-0.527	-0.242	0.572	0.078	1.000			
TN	-0.450	-0.448	0.562	-0.302	0.299	0.552	-0.163	-0.036	0.410	-0.332	0.499	1.000		
Fe	-0.009	-0.530	0.105	0.153	-0.139	0.042	-0.481	-0.555	0.178	-0.379	0.675	0.623	1.000	
Zn	-0.353	0.333	0.319	-0.419	0.434	0.344	0.012	0.145	0.416	0.580	0.679	0.033	0.122	1.000

5. SUMMARY AND CONCLUSIONS

This study investigated the effects of different LULC types and slope position on selected physico-chemical soil properties and soil quality in the Maya-Guddoo subwatershed. Soil fertility and quality can be enhanced through implementation of appropriate management practices which are governed by the assessment of various soil properties and their interactions. These properties collectively determine soil fertility and quality. The study aimed to provide valuable insights for developing targeted land management strategies by assessing soil fertility and quality under different LULC types across slope positions. To achieve this, 27 surface composite soil samples were collected from cultivated, Khat and grazing LULC types across upper, middle and lower slope positions. Key soil properties such as texture, bulk density, total porosity, water content at FC and PWP, AWHC, MC, soil pH, EC, CEC, OM, OC, TN, PBS, exchangeable bases and extractable micronutrients were analyzed. The soil quality index was evaluated for the selected soil quality indicators under different LULC types across slope positions.

The analysis showed a significant variation for most soil properties and SQI except PBS in study area. However, silt and AWHC across LULC types and TN across slope positions showed non-significant differences. Analysis of soil physical properties revealed that grazing LC type, particularly at lower slope position exhibited favorable characteristics. The soil of this LULC type showed better water retention and nutrient storage because of its higher clay content. This conclusion is further supported by lower bulk density and higher total porosity, a well-aerated soil that is favorable for microbial activity and root growth.

In contrast, soil of cultivated LULC type, particularly at upper slopes showed possible soil degradation due to intense farming methods, which have detrimental effect on soil structure and water infiltration, as influenced by lower clay content, higher bulk density and decreased total porosity. These adverse effects were made worse at upper slope positions, which are more susceptible to erosion. The soil under Khat LU type demonstrated mixed results influenced by slope positions, with lower TN and higher AV.P records at lower slope position. Additionally, the moisture content, Calcium and Potassium levels were notably higher at the middle slope position as a result of addition of organic matter, fertilization practices and shading effects provided by the Khat crop.

Soil in the grazing LC type, primarily at lower slope position exhibited the highest levels of organic matter, total nitrogen and several exchangeable bases, reflecting improved soil fertility. The abundance of organic matter is crucial for nutrient cycling, soil structure improvement and microbial activity. These findings emphasize the positive role of grazing in maintaining soil properties, particularly at lower slope positions where organic matter accumulation is facilitated. Soil of cultivated LULC type, especially at upper slope positions frequently displayed the lowest values of crucial soil properties. This suggests nutrient depletion, potentially driven by continuous crop harvesting and exacerbated by erosion on steeper slopes.

The soil quality index (SQI) showed that both LULC types and slope positions significantly impact soil quality. The highest SQI was calculated for soil of Khat LU type at middle slope position, suggesting comparatively better soil quality due to the effects of organic inputs, moisture retention, fertilizer applications and nutrient availability, as farmers in study area prioritize soil fertility in Khat cultivation due to its high economic value, often applying fertilizers and practicing weed control, resulting in the highest SQI value. However, the lowest SQI was also calculated under the soil of the same LULC type at upper slope position, indicating the vulnerability of soil to degradation, particularly in areas that are prone to erosion.

Management practices are a key to improving soil fertility and quality in the study area. This study emphasizes how site-specific land management techniques are crucial to preserving and enhancing soil fertility and quality. In order to reduce the adverse effects of intensive tillage practices on soil quality, cultivated LU type needs careful attention to conserve the soil.

To achieve sustainable agriculture and enhance the soil fertility and quality in Maya-Guddoo subwatershed, the study recommends the evidence-based interventions: contour strip cropping with biochar-compost for erosion control, reduced tillage and nitrogen-fixing hedgerows (*Calliandra/Sesbania*) in Khat cultivation, and a rotational grazing system using to enhance water retention. Furthermore, promoting sustainable grazing practices, addressing nutrient deficiencies in cultivating areas, improving organic matter content in both cultivated and Khat LULC types, strengthened the extension services and consistently monitoring soil fertility and quality to support long-term agricultural productivity and environmental sustainability in Maya-Guddoo subwatershed.

6. REFERENCES

Abraham, J. S., Sripoorna, S., Dagar, J., Jangra, S., Kumar, A., Yadav, K., Singh, S., Goyal, A., Maurya, S., Gambhir, G., Toteja, R., Gupta, R., Singh, D. K., El-Serehy, H. A., Al-Misned, F. A., Al-Farraj, S. A., Al-Rasheid, K. A., Maodaa, S. A. and Makhija, S. 2019. Soil ciliates of the Indian Delhi Region: their community characteristics with emphasis on their ecological implications as se.sitive bio-indicators for soil quality. *Saudi Journal of Biological Sciences*, 26(6), 1305-1313.

Agricultural Transformation Agency (ATA). 2013. Annual report: Transforming agriculture in Ethiopia. Addis Ababa, Ethiopia.

Akbas, F., Gunal, H. and Acir, N. 2017. Spatial variability of soil potassium and its relationship to land use and parent material.

Ali, A., Esayas, A. and Beyene, S. 2010. Characterizing soils of Delbo Wegene watershed, Wolaita Zone, Southern Ethiopia for planning appropriate land management. *Journal of Soil Science and Environmental Management*, 1(8), 184-199.

Al-Kaisi, M. M., Yin, X. and Licht, M. A. 2005. Soil carbon and nitrogen changes as influenced by tillage and cropping systems in some Iowa soils. *Agriculture, Ecosystems and Environment*, 105(4), 635-647.

Alley, M. M. and Vanlauwe, B. 2009. The Role of Fertilizers in Integrated Plant Nutrient Management. *1st edition. International fertilizer industry association,* Paris, France.

Amare, H., Admase, H. and Ewunetu, T. 2024. Influence of land-use types and topographic slopes on the physico-chemical characteristics of soils in Northwestern Ethiopia. *Frontiers in Soil Science*, 4, 1463315.

Amber Anderson. 2023. *Introduction to Soil Science, Micronutrients.* IOWA State University.

Anup, K. C., Bhandari, G., Wagle, S. P. and Banjade, Y. 2013. Status of soil fertility in a community forest of Nepal. *International Journal of Environment*, 1(1), 56-67.

Araba Jemal Ibrahim. 2021. Assessment of Selected Physical and Chemical Properties of Soils under different Land Uses and Slope Positions at Gola Wachu Sub-Watershed, East Hararghe Zone, Ethiopia *(Doctoral dissertation, Haramaya University).*

Armenise, E., Redmile-Gordon, M. A., Stellacci, A. M., Ciccarese, A. and Rubino, P. 2013. Developing a soil quality index to compare soil fitness for agricultural use under different managements in the Mediterranean environment. *Soil and Tillage Research*, 130, 91-98.

Arshad, M.A., Lowery, B. and Grossman, B. 2015. Physical tests for monitoring soil quality, 123–142. In: J.W. Doran and A.J. Jones (Eds.). *Methods for assessing soil quality*, Soil Science Society of America Special Publication 49, SSSA, Madison, WI.

Asefa, T., Ayenew, T. and Tefera, T. 2010. Soil organic carbon and total nitrogen stocks along an altitudinal gradient in the Ethiopian highlands. Soil Use and Management, 26(3), 261-268.

Astier-Calderón, M., Maass-Moreno, M. and Etchevers-Barra, J. 2002. Derivation of soil quality indicators in the context of sustainable agriculture. *Agrociencia*, 36(5), 605-620.

Aweke Gelaw., Singh, B. R. and Lal, R. 2015. Soil quality indices for evaluating smallholder agricultural land uses in Northern Ethiopia. *Sustainability*, 7: 2322-2337.

Ayalew, A. A., Kidana, T. A. and Abebe, E. F. 2023. Effects of Land Management Practice Type and Slope Position on Selected Soil Physico-Chemical Properties in Agamssa Watershed, North Wollo, Ethiopia. https://doi.org/10.20944/preprints202308.0162.v1

Ayoubi, S., Khormali, F., Sahrawat, K. L. and de Lima, A. C. R. 2011. Assessing impacts of land use change on soil quality in dicators in a loessial soil in Golestan Province, Iran, *Journal of Agricultural Science and Technology*, vol. 13, 727–742.

Baath, E. and Anderson, T. H. 2003. Comparison of soil fungal/bacterial ratios in a pH gradient using physiological and PLFA-based techniques. *Soil Biology and Biochemistry*. 35(7), 955-963.

Bahilu Bezabih. 2014. Soil Fertility Status as Affected by Different Land Use Types and Topographic Positions: A Case of Delta Sub-Watershed, Southwestern Ethiopia. *Journal of Biology, Agriculture and Healthcare*, 4(27):91-105.

Bationo A. 2009. Constraints and New Opportunities for Achieving a green Revolution in Sub-Saharan Africa through Integrated Soil Fertility Management.

Beernaert, F. and Bitondo, D. 1990. Simple and practical methods to evaluate analytical data of soil profiles. *INIA, department of land and water.* FAO, 86 (10).

Berhanu Debele. 1980. The physical criteria and their rating proposed for land evaluation in the highland region of Ethiopia. *Land Use Planning and Regulatory Department, Ministry of Agriculture, Addis Ababa, Ethiopia.*

Bernhard, A. 2010. The Nitrogen Cycle: Processes, Players, and Human Impact. *Nature Education Knowledge* 3(10):25.

Beshir, S., Lemeneh, M. and Kissi, E. 2015. Soil fertility status and productivity trends along a toposequence: a case of gilgel gibe catchment in nadda assendabo watershed, southwest Ethiopia. *International Journal of Environmental Protection and Policy*, 3(5), 137-144.

Bindajam, A. A., Mallick, J., AlQadhi, S., Singh, C. K. and Hang, H. T. 2020. Impacts of vegetation and topography on land surface temperature variability over the semi-arid mountain cities of Saudi Arabia. *Atmosphere*, 11(7), 762.

Bizuwork T.D. and Yibekal A. 2020. Optimizingblended (NPSB) and N fertilizer rates for the productivity of Durum wheat (*Triticumturgidum* L. var. durum) in central highlands of Ethiopia. *Cogent Food and Agriculture,* 6, 1–20.

Bockheim, J. G., Gennadiyev, A. N., Hartemink, A. E. and Brevik, E. C. 2014. Soil-forming factors and Soil Taxonomy. Geoderma, 226, 231-237.

Brady, N. C. and Weil, R. R. 2008. The nature and properties of soils. *Pearson Education*.

Braimoh, A. K. and Vlek, P. L. 2008. Impact of land use on soil resources. *In Land use and soil resources Dordrecht: Springer Netherlands* (1-7).

Bronick, C. J. and Lal, R. 2005. Soil structure and management: a review. *Geoderma*, 124(1-2), 3-22.

Buczko, U., Bens, O. and Hüttl, R. F. 2006. Tillage effects on hydraulic properties and macroporosity in silty and sandy soils. *Soil Science Society of America Journal*, 70(6), 1998-2007.

Cantú, M. P., Becker, A., Bedano, J. C. and Schiavo, H. F. 2007. Evaluation of soil quality through the use of indicators and indices. *Soil Science*, 25(2), 173-178.

Caravaca, F., Masciandaro, G. and Ceccanti, B. 2002. Land use in relation to soil chemical and biochemical properties in a semiarid Mediterranean environment. *Soil and Tillage Research*, 68(1), 23-30.

Carter, M. R. 2002. Soil Quality for Sustainable Land Management: Organic Matter and Aggregation Interactions that Maintain Soil Functions, *Agronomy Journal*, 94 (38-47).

Chianu, J. N., Chianu, J. N. and Mairura, F. 2012. Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. *Agronomy for sustainable development*, 32, 545-566.

Das SK. and Varma A. 2011. Role of enzymes in maintaining soil health. *Soil enzymology*. 25-42.

Das, D., Dwivedi, B. S., Datta, S. P., Datta, S. C., Meena, M. C., Agarwal, B. K. and Jaggi, S. 2019. Potassium supplying capacity of a red soil from eastern India after forty-two years of continuous cropping and fertilization. *Geoderma*, 341, 76-92.

Davis K., Nkonya E., Kato E., Mekonnen D.A., Odendo M., Miiro R. and Nkuba J. 2012. Impactof farmer field schools on agricultural productivity and poverty in East Africa. *World Development,* 40, 402–413.

Dec, D., Dörner, J., Becker-Fazekas, O. and Horn, R. 2008. Effect of bulk density on hydraulic properties of homogenized and structured soils. *J. Soil Sci. Plant Nutr*, 8(1), 1-13.

Delelegn, Y. T., Purahong, W., Blazevic, A., Yitaferu, B., Wubet, T., Göransson, H. and Godbold, D. L. 2017. Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. *Scientific Reports*, 7(1), 13602.

Denboba, M. A. 2005. Forest conversion-soil degradation farmers' perception nexus: implications for sustainable land use in the southwest of Ethiopia. *Ecology and Development Series*, no. 26.

Diack, M. and Stott, D. E. 2001. Development of a soil quality index for the Chalmers Silty Clay Loam from the Midwest USA. *Purdue University*: *USDA-ARS National Soil Erosion Research Laboratory*, 550-555.

Dilnesa Bayle, Samuel Feyissa, Solomon Tamiru. 2023. Effects of land use and slope position on selected soil physicochemical properties in Tekorsh Sub-Watershed, East Gojjam Zone, Ethiopia. *Open Agriculture*, 8(1) doi: 10.1515/opag-2022-0147

Doran, J. W. and Zeiss, M. R. 2000. Soil health and sustainability: managing the biotic component of soil quality. *Applied soil ecology*, 15(1), 3-11.

Eldor P. 2007. Soil Microbiology, Ecology and Biochemistry. Tercera ed. Eldor P, editor. Chennai, India: *Academic Press.*

Elizabeth Stockdale. 2023. Fact Sheets Making Sense of Chemical Indicators. (Newcastle University, UK).

Erkossa, T., Laekemariam, F., Abera, W. and Tamene, L. 2022. Evolution of soil fertility research and development in Ethiopia: From reconnaissance to data-mining approaches. *Experimental Agriculture.* 58:e4. https://doi.org/10.1017/S0014479721000235

Ermias Teferi, E. T., Woldeamlak Bewket, W. B. and Belay Simane, B. S. 2016. Effects of land use and land cover on selected soil quality indicators in the headwater area of the Blue Nile basin of Ethiopia.

Eshetu, M. and Wogi, L. 2024. Effects of Slope Position on Soil Physicochemical Properties of Cultivated Land Use Type in Danka Watershed of Dinsho District, Bale Highland, Oromia, Southeast Ethiopia. *International Journal of Plant & Soil Science*, 36(5), 831-846.

Eshetu, M., Wogi, L. and Demissie, N. 2024. Soil Fertility Assessment and Mapping under Different Land Use Types along Toposequence at Danka Watershed in Dinsho Districts of Bale Highland Oromia, Southeastern Ethiopia. *International Journal of Plant & Soil Science*, 36(5), 847-872.

Ethiopian Soil Information System (EthioSIS). 2014. Soil Analysis Report. Agricultural Transformation Agency (Unpublished).

Eyasu E., Beyene T. and Tewodros T. 2020. Effect of blended fertilizer application on bread wheat yield, agronomic efficiency and profitability on Nitisols of Southern Ethiopia. *South African Journal of Plant and Soil*, 37, 292–299.

Eyasu Elias. 2017. Characteristics of Nitisol profiles as affected by land use type and slope class in some Ethiopian highlands. *Environmental Systems Research*, 6(1):1-15.

FAO (Food and Agriculture Organization of the United Nations). 2023. Global Soil Partnership/Work Areas/ Soil Fertility.

FAO (Food and Agriculture Organization). 2002. The Comprehensive Africa Agriculture Development Programme (CAADP) of NEPAD.

FAO (Food and Agriculture Organization). 2006. Plant nutrition for food security: A guide for

FAO and ITPS. 2015. Status of the World's Soil Resources (SWSR)- Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

Filippelli, G. M. 2017. The global phosphorus cycle. In Lal R. and Stewart B. A. (Eds.), Soil Phosphorus (1–21). *Boca Raton: CRC Press.*

Foth, H.D. and Ellis, B.G. 1997. Soil Fertility. *2nd Edition. Lewis Publication, Boca Raton, Florida.* 290p.

Fuentes, J. P., Flury, M. and Bezdicek, D. F. 2004. Hydraulic properties in a silt loam soil under natural prairie, conventional till, and no-till. *Soil Science Society of America Journal*, 68(5), 1679-1688.

Gebreyesus Brhane Tesfahunegn, G. B. T. 2014. Soil quality assessment strategies for evaluating soil degradation in northern Ethiopia.

Geisseler, D. and Scow, K. M. 2014. Long-term effects of mineral fertilizers on soil microorganisms - a review. *Soil Biology and Biochemistry*. 75, 54-63.

Getachew Fisseha, Heluf Gebrekidan.2007. Characterization and fertility status of the soils of Ayehu research substation, Northwestern highlands of Ethiopia.

Gete Zelleke, Getachehu Agegnehu, Dejene Abera, Shahidur Rashid. 2010. Fertilizer and soil fertility potential in Ethiopia constraints opportunities for enhancing the system.

Ghaemi, M., Astaraei, A. R., Emami, H., Nassiri Mahalati, M. and Sanaeinejad, S. H. 2014. Determining soil indicators for soil sustainability assessment using principal component analysis of Astan Quds-east of Mashhad-Iran. *Journal of soil science and plant nutrition*, 14(4), 1005-1020.

Gholamhosseinian, A., Bashtian, M. H. and Sepehr, A. 2022. Soil quality: Concepts, importance, indicators, and measurement. *In Soils in Urban Ecosystem*, 161-187. Singapore: Springer Singapore.

Girmay, G., Singh, B. R., Mitiku, H., Borresen, T. and Lal, R. 2008. Carbon stocks in Ethiopian soils in relation to land use and soil management. *Land Degradation & Development*, 19(4), 351-367.

GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit). 2020. Integrated Soil Fertility Management Project (ISFM) 9th Progress Report (01 July 2019 to 30 June 2020). Addis Ababa.

Göl, C., and Yilmaz, H. 2017. The effect of land use type/land cover and aspect on soil properties at the Gökdere catchment in northwestern Turkey. *Šumarski list*, 141(9-10), 459-467.

Graber, E. R., Singh, B., Hanley, K. and Lehmann, J. 2017. Determination of cation exchange capacity in biochar. *Biochar: A guide to analytical methods*, 74-84.

Gregory, P. J., Simmonds, L. P. and Pilbeam, C. J. 2000. Soil type, climatic regime, and the response of water use efficiency to crop management. *Agronomy Journal*, 92(5), 814-820.

Gupta, P.K. 2004. *Soil, Plant, Water and Fertilizer Analysis*. *Shyam Printing Press,* Agrobios (India).

Gutiérrez, V., Pinzón, Á., Casas, J. and Martínez, M. M. 2008. Determination of soil cellulolytic activity from Stevia rebaudiana Bertoni crops. *Colombian Agronomy,* 26(3), 497-504.

Håkansson, I. and Lipiec, J. 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. *Soil and Tillage Research*, 53(2), 71-85.

Hansong Zhu, Haiqiang Li, Chenglong Liang, Xingchen Chang, Xiaorong Wei, Xiaoning Zhao. 2022. Spatial Variation in Soil Physico-Chemical Properties along Slope Position in a Small Agricultural Watershed Scale. *Agronomy,* 12(10):2457-2457.

Harris, R. F., Karlen, D. L. and Mulla, D. J. 1997. A conceptual framework for assessment and management of soil quality and health. *Methods for assessing soil quality*, 49, 61-82.

Havlin, J.L., Tisdale, S.L., Nelson, W.L. and Beaton, J.D. 1999. *Soil Fertility and Fertilizers, 6th edition*. Macmillan Publishing Company, New York, USA. pp. 85-196.

Hazelton, P. and Murphy, B. 2007. *Interpreting soil test results: What do all the numbers mean? 2nd Edition*. CSIRO Publishing. 152.

Heluf Gebrekidan, Yohannes Ulloro. 1997. Soil and water conservation studies on soils of Hararge highlands, Eastern Ethiopia, Haramaya University, Haramaya.

Hillel, D. 1980. *Fundamentals of soil physics*. Academic Press, Inc., London.

Hoffland, E., Kuyper, T.W. and Comans, R.N.J. 2020. Eco-functionality of organic matter in soils. *Plant Soil* 455, 1–22.

Horn, R. and Smucker, A. 2005. Structure formation and its consequences for gas and water transport in unsaturated arable and forest soils. *Soil Till. Res.* 82, 5-14.

Indoria, A. K., Sharma, K. L. and Reddy, K. S. 2020. Hydraulic properties of soil under warming climate. *In Climate change and soil interactions.* Elsevier. 473-508.

Ishaq, S., Begum, F. and Ali, K. 2015. Assessment of soil quality under different land use practices in Altit Valley, Hunza Nagar,Gilgit-Baltistan. *Journal of Biodiversity and Environmental Sciences*, 6(1), 454–459.

Jaiswal, D. K., Verma, J. P., Prakash, S., Meena, V. S. and Meena, R. S. 2016. Potassium as an important plant nutrient in sustainable agriculture: a state of the art. *Potassium solubilizing microorganisms for sustainable agriculture*, 21-29.

Jangir, C. K., Kumar, S. and Meena, R. S. 2019. Significance of soil organic matter to soil quality and evaluation of sustainability. *Sustainable agriculture. Scientific Publisher, Jodhpur*, 357-381.

Jones, J.B. 2003. *Agronomic Handbook: Management of Crops, Soils and their fertility*. CRC Press LLC, Boca Raton, FL, USA. 482.

Kandeler, E., Mosier, A. R., Morgan, J. A., Milchunas, D. G., King, J. Y., Rudolph, S. and Tscherko, D. 2006. Response of soil microbial biomass and enzyme activities to the transient elevation of carbon dioxide in semi-arid grassland. *Soil Biology and Biochemistry*, 38(8), 2448-2460.

Karlen, D. L., Andrews, S. S. and Doran, J. W. 2003. Soil quality: current concepts and applications, *Advances in Agronomy*, vol. 74, 1–40.

Karlen, D. L., Andrews, S. S. and Wienhold, B. J. 2004. Soil quality, fertility and health-historical context, status and perspectives. *In Managing soil quality: challenges in modern agriculture* (pp. 17-33). Wallingford UK: CABI Publishing.

Karlen, D. L., Andrews, S. S., Weinhold, B. J. and Doran, J. W. 2003. Soil quality: Humankind's foundation for survival a research editorial by conservation professionals. *Journal of Soil and Water Conservation*, 58(4), 171-179.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F. and Schuman, G. E. 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). *Soil Science Society of America Journal*, 61(1), 4-10.

Karlen, D. L., Stott, D. E., Cambardella, C. A., Kremer, R. J., King, K. W. and McCarty, G. W. 2014. Surface soil quality in five midwestern cropland Conservation Effects Assessment Project watersheds. *Journal of soil and water conservation*, 69(5), 393-401.

Karlen, D. L., Wollenhaupt, N. C. and Erbach, D. C. 1994. Crop residue effects on soil quality following 10-years of no-till corn, *Soil and Tillage Research*, 31(2-3).

Kay B. D. and Angers D. A. 1999. *Soil structure, in Handbook of Soil Science*, M. E. Summer, Ed., 229–269, CRC Press, New York, NY, USA.

Kepp, J., Dannenmann, M., Kiese, R., Pacay, N., Schulz, S., Schweizer, S. and Schwärzler, T. 2024. *Grazing dominantly regulates top soil organic carbon and nitrogen stocks in grasslands* (No. EGU24-10411). Copernicus Meetings.

Kibebew Kibret. 2014. A final report on Characterization of Agricultural Soils in CASCAPE Intervention woredas in Eastern Region.

Kibret Ketema, Husein Abro, Solomon Ayele. 2022. Assessment of Major Fruit Crops Production and Marketing Systems in East Hararghe Zone of Oromia Region, Ethiopia.

Kinnell, P. I. A. 2000. The effect of slope length on sediment concentrations associated with side-slope erosion. *Soil Science Society of America Journal*, 64(3), 1004-1008.

Lal R. 2011. Organic Matter Effects on Soil Physical Properties and Processes. In: Gliński, J., Horabik, J., Lipiec, J. (eds) Encyclopedia of Agrophysics. *Encyclopedia of Earth Sciences Series. Springer, Dordrecht.*

Lal, R. 1991. Soil structure and sustainability. *Journal of Sustain. Agric.* 1, 67 – 92.

Lal, R. 2001. Soil degradation by erosion. *Land Degradation and Development,* 12(3), 191-207.

Landon, J.R. (Ed.). 1991. Booker tropical soil manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. *Long man Scientific and Technical, Essex, New York*. 474.

Lema, B., Mesfin, S., Kebede, F., Abraha, Z., Fitiwy, I. and Haileselassie, H. 2019. Evaluation of soil physical properties of long-used cultivated lands as a deriving indicator of soil degradation, north Ethiopia. *Physical Geography*, 40(4), 323-338.

Li Y., Tremblay, J., Bainard, L. D., Cade-Menun, B. and Hamel, C. 2019b. Long-term effects of nitrogen and phosphorus fertilization on soil microbial community structure and function under continuous wheat production. *Environmental Microbiology.*

Li, X. and Chen, Z. 2004. Soil microbial biomass C and N along a climatic transect in the Mongolia steppe. *Biology and Fertility of Soils.* 39:344-351.

Lilienfein, J., Wilcke, W., Ayarza, M.A., Vilela, L., Lima, S.D.C. and Zech, W. 2000. Chemicalfraction of phosphorus, sulfur, and molybdenum in Brazilian savannah Oxilsols underdifferent land uses. *Geoderma*, 96:31-46.

Manggoel, W., Da'ar, J., Loks, N. and Mamzing, D. 2014. Evaluation of some soil properties at Kuru-Jos in the Nigerian Northern Guinea Savanna ecological zone. *Nigerian Journal of Crop Science*, 2(1), 13-17.

Maria, Martinez, Gutiérrez-Romero, V., Jannsens, M., Ortega-Blu, Rodrigo. 2010. Biological soil quality indicators: a review. *Current Research, Technology and Education Topics in Applied Microbiology and Microbial Biotechnology*. 319-328.

Marriott, E. E., and Wander, M. M. 2006. Total and labile soil organic matter in organic and conventional farming systems. *Soil Science Society of America Journal*, 70(3), 950-959.

Martín, M. Á., Reyes, M. and Taguas, F. J. 2017. Estimating soil bulk density with information metrics of soil texture. *Geoderma*, 287, 66-70.

Marx, ES, Hart, J and Stevens, RG. 1999. Soil Testing Interpretation Guide, Oregon State University, Corvallis.

Masto, R. E., Chhonkar, P. K., Singh, D. and Patra, A. K. 2008. Soil quality response to long-term nutrientand crop management on a semi-arid Inceptisol.

Mausbach M. J. and Seybold C. A. 1998. Assessment of soil quality, *Soil Quality and Agricultural Sustainability*, R. Lal, Ed., 33–43, Sleeping Bear Press, Mich, USA.

Mei Xuemei, Lan Ma, Qingke Zhu, Wang Shu, Zhang Dong, Yu Wang. 2018. Responses of soil moisture to vegetation restoration type and slope length on the loess hillslope. *Journal of Mountain Science*, 15(3):548-562.

Miao Wang, Chu Zhang, Xiaoping Xin, Ke Z Bai, Xiaoyu Zhu, Ruirui Yan. 2023. Impacts of Grazing Disturbance on Soil Nitrogen Component Contents and Storages in a Leymus chinensis Meadow Steppe. *Agronomy*, 13(6), 1574.

MoANR (Ministry of Agriculture and Natural Resource). 2017. Ethiopia is Transitioning into the Implementation of Soil Test-Based Fertilizer Use Systems.

Moffat A. J. 2003. Indicators of soil quality for UK forestry, *Forestry*, vol. 76, 1–22.

Moges Awdenegest, Melku Dagnachew, Fantaw Yimer. 2013. Land Use Effects on Soil Quality Indicators: A Case Study of Abo-Wonsho Southern Ethiopia. *Applied and Environmental Soil Science.* (2013), 9.

Moges, A., Dagnachew, M., and Yimer, F. 2013. Land Use Effects on Soil Quality Indicators: A Case Study of Abo-Wonsho Southern Ethiopia. *Applied and Environmental Soil Science*, 2013(1), 784989.

Mohammadi, K., Heidari, G., Khalesro, S. and Sohrabi, Y. 2011. Soil management, microorganisms and organic matter interactions: A review. *African Journal of Biotechnology*, 10(86), 19840.

Molla, E., Getnet, K. and Mekonnen, M. 2022. Land use change and its effect on selected soil properties in the northwest highlands of Ethiopia. *Heliyon*, 8(8).

Moncada, MP, Gabriels, D, Cornelis, W, Lobo, D. 2013. Comparing aggregate stability tests for soil physical quality indicators. *Land Degradation and Development*.

Moral, F. J. and Rebollo, F. J. 2017. Characterization of soil fertility using the Rasch model. *Journal of soil science and plant nutrition*, 17(2), 486-498.

Nabiollahi, K., Golmohamadi, F., Taghizadeh-Mehrjardi, R., Kerry, R. and Davari, M. 2018. Assessing the effects of slope gradient and land use change on soil quality degradation through digital mapping of soil quality indices and soil loss rate. *Geoderma*, 318, 16-28.

Nakajima, T., Lal, R. and Jiang, S. 2015. Soil quality index of a crosby silt loam in central Ohio. *Soil and Tillage Research*, 146, 323-328.

Natural Resources Conservation Service. 2011. U.S. Department of Agriculture, Physical Tests for Monitoring Soil Quality.

Natural Resources Conservation Service. 2011. U.S. Department of Agriculture “Soil Quality for Environmental Health”. http://soilquality.org/home.html

Nieder, R. and Benbi, D. K. 2008. Organic matter and soil quality. *Carbon and Nitrogen in the Terrestrial Environment*, 113-135.

Norris, C. E., Quideau, S. A., Landhausser, S. M., Drozdowski, B., Hogg, K. E. and Oh, S. W. 2018. Assessing structural and functional indicators of soil nitrogen availability in reclaimed forest ecosystems using 15N-labelled aspen litter. *Canadian Journal of Soil Science.* 98(2), 357-368.

Nwachokor, M. A., Uzu, F. O. and Molindo, W. A. 2009. Variations in physicochemical properties and productivity implications for four soils in the derived savannah of southern Nigeria. *American-Eurasian Journal of Agronomy*, 2(3), 124-129.

Obalum, S. E., Chibuike, G. U., Peth, S. and Ouyang, Y. 2017. Soil organic matter as sole indicator of soil degradation. *Environmental Monitoring and Assessment*. 189, 1-19.

O'Geen, A. T. 2013 Soil Water Dynamics. *Nature Education Knowledge* 4(5):9.

Oldfield, E. E., Wood, S. A. and Bradford, M. A. 2018. Direct effects of soil organic matter on productivity mirror those observed with organic amendments. *Plant and soil*, 423, 363-373.

Olsen, S.R., Cole, C.V., Watanable, F.S. and Dean, L.A. 1954. Estimation of variable phosphorus in soil by extraction with sodium bicarbonate. *USDA Circular.* 939: 1-19.

Osman, K.T. 2013. Physical Properties of Soil. *In: Soils. Springer, Dordrecht.*

O'Sullivan, L., Bampa, F., Knights, K. and Creamer, R. E. 2017. Soil protection for a sustainable future: options for a soil monitoring network for Ireland. *Soil Use and Management*, 33(2), 346-363.

Parkinson, D. and Coleman, D. 1991. Microbial communities, activity and biomass. *Agriculture Ecosystems and Environment.* 34:3-33.

Pham, T. G., Nguyen, H. T. and Kappas, M. 2018. Assessment of soil quality indicators under different agricultural land uses and topographic aspects in Central Vietnam, *International Soil and Water Conservation Research*, 6(4), 280–288.

Pimentel, D. 1995. Soil erosion: A global environmental problem. *Science*, 267(5201), 1139-1144.

Pramod Ghimire, Uchita Lamichhane, Sandesh Bolakhe, Chun-Hung, Jeb Lee. 2023. Impact of Land Use Types on Soil Organic Carbon and Nitrogen Stocks: A Study from the Lal Bakaiya Watershed in Central Nepal. *International Journal of Forestry Research*, 2023(1), 9356474.

Rahal, N. S. and Alhumairi, B. A. J. 2019. Modelling of soil cation exchange capacity for some soils of east gharaf lands from mid-Mesopotamian plain. *International journal of environmental science and technology*, 16(7), 3183-3192.

Rakesh, K. Maikhur and Kottapalli, S Rao. 2012. Soil Quality and Soil Health. Review. *International Journal of Ecology and Environmental Sciences.*

Ramesh, M. N., Ebrahimi, E. and Bayat, H. 2024. Investigating the Long-Term Effect of Livestock Grazing, Slope Location, and Sampling Depth on Soil Moisture Characteristic Curves. *Rangeland Ecology & Management*, 93, 123-135.

Reynolds, W. D., Bowman, B. T., Drury, C. F., Tan, C. S. and Lu, X. 2002. Indicators of good soil physical quality: density and storage parameters. *Geoderma*, 110, 131–146.

Roy, R. N., Misra, R. V., Lesschen, J. P. and Smaling, E. M. A. 2003. *Assessment of soil nutrient balance: approaches and methodologies* (No. 14). Food & Agriculture Org.

Sahil, S., Shubham, Balara, L. and Shilpa, K. 2023. Soil Quality Indicators: A Comprehensive Review. *International Journal of Plant and Soil Science*, 35(22), 315-325.

Saleh, A. M., Elsharkawy, M. M., AbdelRahman, M. A. and Arafat, S. M. 2021. Evaluation of soil quality in arid western fringes of the Nile Delta for sustainable agriculture. *Applied and Environmental Soil Science,* 2021(1), 1434692.

Sanchez, P.A., Sheperd, K.D., Soul, M.J., Place, F.M., Buresh, R.J., Izac, A.M.N., Mokwunye, A.U, Kwesiga, F.R., Ndirtu, C.G. and Woomer, P.L. 1997. Soil fertility replenishment in Africa. *An investment in natural resource capital,* 1-46.

Sattar, A., Naveed, M., Ali, M., Zahir, Z. A., Nadeem, S. M., Yaseen, M., Meena, V. S., Farooq, M., Singh, R., Rahman, M. and Meena, H. N. 2019. Perspectives of potassium solubilizing microbes in sustainable food production system: a review. *Applied Soil Ecology,* 133, 146-159.

SEP (Socio-economic profile). 2006. Socio-economic profile of the East Hararghe Zone, Government of Oromia Region.

Shannon, D. Sen, A. and Johnson, D. 2002. A comparative study of the microbiology of soil structure under organic and conventional regimes. *Soil Use Manage.* 18:274-283.

Sharma, B. D., Mukhopadhyay, S. S. and Sawhney, J. S. 2006. Distribution of potassium fractions in relation to landforms in a Himalayan catena: (Verteilung von Kaliumfraktionen von Bodenarten innerhalb einer Himalaya–Catena). *Archives of Agronomy and Soil Science,* 52(4), 469-476.

Shiri, J., Keshavarzi, A., Kisi, O., Iturraran-Viveros, U., Bagherzadeh, A., Mousavi, R. and Karimi, S. 2017. Modeling soil cation exchange capacity using soil parameters: Assessing the heuristic models. *Computers and Electronics in Agriculture,* 135, 242-251.

Shukla, M.K., Lal, R. and Ebinger, M. 2006. Determining soil quality indicators by factor analysis. *Soil & Tillage Research* 87, 194-204.

Sigua, G. C., Coleman, S. W., Albano, J. and Williams, M. 2011. Spatial distribution of soil phosphorus and herbage mass in beef cattle pastures: effects of slope aspect and slope position. *Nutrient cycling in Agroecosystems,* 89, 59-70.

Singh A. K. and Pathak S. K. 2018. Potassium in tea (Camellia sinensis (L) O. Kuntze) cultivation from soil to cup quality - a review. *Agricultural Reviews*, 39(1), 40-47.

Sishekanu, M., Mabengwa, M., Makungwe, M., Gondwe, B., Banda, F., Siulemba, G. and Mutegi, J. 2015. Integrated Soil Fertilty Management Training Manual for Zambia's Agricultural Extension Workers. *The Zambian Soil Health Consortium*.

Solomon Muleta. 2002. Soil erosion and sedimentation analysis of Lake Alemaya Catchment MSc thesis, Alemaya University. Ethiopia.

Stockdill S. Effects of introducted earthworms on the productivity of New Zealand pastures. *Pedobiologia.* 1982;24(1):2935.

Sumon Datta, Saleh Taghvaeian, Jacob Stivers. 2018. Understanding Soil Water Content and Thresholds for Irrigation Management.

Tabor, N. J., Myers, T. S. and Michel, L. A. 2017. Sedimentologist's guide for recognition, description, and classification of paleosols. In K. E. Zeigler & W. G. Parker (Eds.), *Terrestrial depositional systems*: deciphering complexities through multiple stratigraphic methods (165–208).

Tadesse, A. and Hailu, W. 2024. Causes and consequences of land degradation in Ethiopia: A Review. *International Journal of Science and Qualitative Analysis*, 10(1), 10-21.

Tamirie Hawando, Heluf Gebrekidan, Yohannes Uloro. 1986. Summary results on completed soil science research projects on major soil types in Hararghe Highlands, Eastern Ethiopia.

Teferi, E, Bewket, W, and Simane, B. 2016. Effects of land use and land cover on selected soil quality indicators in the headwater area of the Blue Nile basin of Ethiopia, *Environmental Monitoring and Assessment*, 188(2), 1–12.

Tejada, M., Hernandez, M. T., and Garcia, C. 2006. Application of two organic amendments on soil restoration: effects on the soil biological properties. *Journal of Environmental Quality*, 35(4), 1010-1017.

Tesfahunegn, G. B. 2016. Soil quality indicators response to land use and soil management systems in northern Ethiopia's catchment. *Land Degradation & Development*, 27(2), 438-448.

Tilahune, A., Endrias, G. and Takele, B. 2007. Reversing the degradation of arable land in Ethiopian highlands, Managing Africa's soil. No. 23, IIED-London.

USDA (United States Department of Agriculture). 2006. Soil Quality Institute. Natural Resources Conservation Service. Available at http://soils.usda.gov/sqi/.

USDA (United States Department of Agriculture). 2014. Biological Indicators and Soil Functions. Natural Resources Conservation Service. Available at https://www.nrcs.usda.gov/sites/default/files/202210/biological_indicators_overview.pdf

Usharani, K. V., Roopashree, K. M. and Naik, D. 2019. Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture.

Usmael Mohammed, Kibebew Kibret, Muktar Mohammed, Alemayehu Diriba. 2018. Soil Fertility Assessment and Mapping of Becheke Sub-Watershed in Haramaya District of East Hararghe Zone of Oromia Region, Ethiopia. *Journal of Natural Sciences Research*, 8(20).

Vanlauwe B., Bationo A., Chianu J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L. and Sanginga, N. 2010. Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture*, 39,17–24.

Velayutham, M. and Bhattacharyya, T. 2000. *Soil resource management*, pp.3-4. Natural Resource Management for Agricultural Production in India, 14-18, New Delhi.

Vinhal-Freitas, I. C., Corrêa, G. F., Wendling, B., Bobuľská, L. and Ferreira, A. S. 2017. Soil textural class plays a major role in evaluating the effects of land use on soil quality indicators. *Ecological indicators*, 74, 182-190.

Wajahat, N., Sajida, P. and Iftikhar, S. 2006. Status of micronutrients in soils of district Bhimber. *Journal of Agricultural and Biological Science*, 1(2): 35-40.

Wales M, Le Breton R. 2001. Dynamics and diversity, soil fertility and farming livelihoods in Africa: *Case studies from Ethiopia, Mali and Zimbabwe*. UK and USA.

Wang, J., Yang, H., Liu, S., Schuler, J., Wang, Y. and Luan, J. 2023. Nitrogen-fixing plants enhance and stabilize rhizospheric soil organic carbon in tropical rainforests, Hainan Island, China. *Forest Science*, 69(6), 653-664.

Wasihun Mengiste, Muktar Mohammed, Teshome Yitebarek. 2015. Evaluation of the Effect of Land Use Types on Selected Soil Physico-Chemical Properties in Itang-Kir Area of Gambella Region, Ethiopia. *Journal of Biology, Agriculture and Healthcare*, 5(13):128-138.

Williams, PT. 2005. *Waste Treatment and Disposal*. 2nd ed. John Wiley and Sons Ltd, England.

Woldemariam Seifu, Eyasu Elias and Girmay Gebresamuel. 2020. The effects of land use and landscape position on soil physicochemical properties in a semiarid watershed, northern Ethiopia. *Applied and Environmental Soil Science*, 2020 (1), 8816248.

Wood, E. A., Case, S. J., Collins, S. L., Stark, H. and Wilfong, T. 2024. From traditional to transactional: exploration of khat use in Ethiopia through an interpretative phenomenological analysis. *BMC Public Health*, 24(1), 1887.

Yan, N., Marschner, P., Cao, W., Zuo, C. and Qin, W. 2015. Influence of salinity and water content on soil microorganisms. *International Soil and Water Conservation Research.*

Yared Mulat. 2018. *Soil Characterization, Classification and Quality Assessment in Kersa Sub-Watershed, Eastern Ethiopia* (Doctoral Dissertation, Haramaya University).

Yennawar, VB, Bhosle, AB and Khadke, PA. 2013. Soil Analysis and Its Environmental Impact on Nanded City, Maharastra. *Research Front,* 1(1), 65-70.

Yimer, F., Messing, I., Ledin, S. and ABdelkadir, A. 2008. Effects of different land use types on infiltration capacity in a catchment in the highlands of Ethiopia. *Soil use and management*, 24(4), 344-349.

Yirga, C. and Hassan, R. M. 2010. Social costs and incentives for optimal control of soil nutrient depletion in the central highlands of Ethiopia. *Agricultural Systems*, 103(3), 153-160.

Yitbarek, T., Gebrekidan, H., Kibret, K. and Beyene, S. 2013. Impacts of land use on selected physicochemical properties of soils of Abobo area, western Ethiopia, *Agriculture, Forestry and Fisheries*, 2(5), 177.

Yoseph Indale, Delelegn Terefe, Witoon P. , Amila B., Birru Yitaferu,Tesfaye Wubet ,Hans G.and Douglas L. 2017. Changes in land use alter soil quality and aggregate stability in the highlands of northern Ethiopia. *Scientific Reports,* 7(1), 13602.

Zeleke, G. 2010. A study on mountain externalities in Ethiopia. *Final report, FAO Sustainable Agriculture and Sustainable Development, Mountain Policy Project, Addis Ababa*.

Zhao, F. and Xu, K. 2016. Biodiversity patterns of soil ciliates along salinity gradients. *European Journal of Protistology*. 53, 1-10.

Zhe Zhang, Xiaoyu Song. 2023. Nanoscale soil-water retention mechanism of unsaturated clay via MD and machine learning. *Computers and Geotechnics*, 163:105678-105678. doi: 10.1016/j.compgeo.2023.105678

Zhi Li, Wenzhao Liu and Qiuxian Wang. 2008. Effects of land use type and slope position on soil physical properties in loess tableland area. *Journal of Applied Ecology*, 19(6):1303-1308.

Zingore, S., Mutegi, J., Agesa, B., Tamene, L. and Kihara, J. 2015. Soil degradation in Sub-Saharan Africa and crop production options for soil rehabilitation.

7. APPENDIX

Appendix Table 1: GPS points of soil sampling sites of different LULC types along slope positions in Maya-Guddoo subwatershed

LULC Types	Slope Position	Specific Place	Rep.	Longitude	Latitude	Altitude (m)	Slope (°)
Khat	Upper	Ganda Abdi	1	9°23'01.164"N	42°00'28.580"E	2061	4.5
Khat	Upper	Ganda Kalu	2	9°22'52.729"N	42°00'27.603"E	2076	5
Khat	Upper	Ganda Kalu	3	9°22'45.432"N	42°00'31.013"E	2050	4
Khat	Middle	Ganda Jalaba	1	9°23'13.064"N	42°00'39.590"E	2036	5.5
Khat	Middle	Ganda Jalaba	2	9°23'04.484"N	42°00'40.663"E	2029	5
Khat	Middle	Ganda Kalu	3	9°22'40.200"N	42°00'35.093"E	2030	5.5
Khat	Lower	Ganda Jalaba	1	9°23'15.010"N	42°00'50.640"E	1996	2
Khat	Lower	Ganda waday	2	9°23'02.266"N	42°00'54.392"E	1997	2
Khat	Lower	Ganda Kalu	3	9°22'47.292"N	42°00'56.967"E	2001	2
Cultivated	Upper	Ganda Abdi	1	9°23'00.000"N	42°00'26.650"E	2077	5
Cultivated	Upper	Ganda Kalu	2	9°22'51.779"N	42°00'27.763"E	2075	5
Cultivated	Upper	Ganda Kalu	3	9°22'45.985"N	42°00'33.344"E	2052	3.5
Cultivated	Middle	Ganda Jalaba	1	9°23'15.570"N	42°00'41.068"E	2024	5
Cultivated	Middle	Ganda Abdi	2	9°23'01.794"N	42°00'36.842"E	2036	6
Cultivated	Middle	Ganda Kalu	3	9°22'43.030"N	42°00'36.230"E	2044	5.5
Cultivated	Lower	Ganda Jalaba	1	9°23'13.893"N	42°00'52.493"E	1988	2
Cultivated	Lower	Ganda Jalaba	2	9°23'05.393"N	42°00'54.363"E	1996	3
Cultivated	Lower	Ganda Dere	3	9°22'42.841"N	42°01'00.120"E	1996	3
Grazing	Upper	Ganda Abdi	1	9°23'05.986"N	42°00'22.752"E	2076	5
Grazing	Upper	Ganda Kalu	2	9°22'56.931"N	42°00'26.057"E	2078	5
Grazing	Upper	Ganda Kalu	3	9°22'45.205"N	42°00'33.269"E	2049	3
Grazing	Middle	Ganda Jalaba	1	9°23'17.277"N	42°00'45.666"E	2011	5
Grazing	Middle	Ganda Jalaba	2	9°23'04.843"N	42°00'39.511"E	2041	5.5
Grazing	Middle	Ganda Kalu	3	9°22'50.916"N	42°00'36.189"E	2048	5.5
Grazing	Lower	Ganda Jalaba	1	9°23'12.780"N	42°00'55.963"E	1991	2
Grazing	Lower	Ganda Jalaba	2	9°23'08.345"N	42°00'56.023"E	1995	2
Grazing	Lower	Ganda Kalu	3	9°22'52.376"N	42°00'57.779"E	1997	2

Appendix Table 2: The ANOVA summary of physical properties of soil in study area

Soil Parameter	Sources of Variation	Df	SS	MS	F Value	P-value	Significance
Sand	LULC Types	2	152.0	76.00	41.88	$1.70*10^{-7}$	HS(P<0.001)
	Slope Position	2	622.2	311.11	171.43	$1.91*10^{-12}$	HS(P<0.001)
	LULC*SP	4	343.1	85.78	47.27	$2.61*10^{-9}$	HS(P<0.001)
	Residuals	18	32.7	1.81			
Silt	LULC Types	2	0.52	0.26	0.35	0.71	NS
	Slope Position	2	15.63	7.82	10.55	$9.29*10^{-4}$	HS(P<0.001)
	LULC*SP	4	14.82	3.70	5.00	0.006888	S (P<0.05)
	Residuals	18	13.33	0.74			
Clay	LULC Types	2	168.5	84.26	54.17	$2.42*10^{-8}$	HS(P<0.001)
	Slope Position	2	442.3	221.15	142.17	$9.40*10^{-12}$	HS(P<0.001)
	LULC*SP	4	362.8	90.70	58.31	$4.65*10^{-10}$	HS(P<0.001)
	Residuals	18	28.0	1.56			
$\boldsymbol{p}$b	LULC Types	2	0.009	0.004	13.65	$2.47*10^{-4}$	HS(P<0.001)
	Slope Position	2	0.074	0.037	113.77	$6.11*10^{-11}$	HS(P<0.001)
	LULC*SP	4	0.30	0.075	229.85	$3.49*10^{-15}$	HS(P<0.001)
	Residuals	18	0.006	0.0003			
Porosity	LULC Types	2	13.2	6.62	14.13	$2.04*10^{-4}$	HS(P<0.001)
	Slope Position	2	104.7	52.37	111.71	$7.12*10^{-11}$	HS(P<0.001)
	LULC*SP	4	424.4	106.11	226.37	$3.99*10^{-15}$	HS(P<0.001)
	Residuals	18	8.4	0.47			
FC	LULC Types	2	45.8	22.88	18.11	$4.91*10^{-5}$	HS(P<0.001)
	Slope Position	2	179.8	89.92	71.15	$2.84*10^{-9}$	HS(P<0.001)
	LULC*SP	4	762.0	190.50	150.74	$1.41*10^{-13}$	HS(P<0.001)
	Residuals	18	22.7	1.26			
PWP	LULC Types	2	45.7	22.85	26.52	$4.30*10^{-6}$	HS(P<0.001)
	Slope Position	2	44.8	22.40	26.01	$4.90*10^{-6}$	HS(P<0.001)
	LULC*SP	4	429.9	107.47	124.77	$7.27*10^{-13}$	HS(P<0.001)
	Residuals	18	15.5	0.86			
AWHC	LULC Types	2	5.20	2.60	1.85	0.185	NS
	Slope Position	2	52.76	26.38	18.83	$3.87*10^{-5}$	HS(P<0.001)
	LULC*SP	4	58.21	14.55	10.39	$1.53*10^{-4}$	HS(P<0.001)
	Residuals	18	25.22	1.40			
MC	LULC Types	2	144.1	72.03	191.05	$7.55*10^{-13}$	HS(P<0.001)
	Slope Position	2	5.6	2.80	7.43	0.0044	S (P<0.05)
	LULC*SP	4	929.1	232.3	616.07	$<2*10^{-16}$	HS(P<0.001)
	Residuals	18	6.8	0.38			

Df=Degree of freedom; HS=Highly significant; MS=Mean squares; NS=Non-significant; SS=Sum of squares; S=Significant; LULC*SP=Interaction effect of LULC types and Slope Positions.

Appendix Table 3: Ratings of bulk density and particle size distribution for a given soil

Rating	ρb (g/cm^3)	Rating	Precent of either silt, clay or sand
Very low	<1.0	Very low	<10
Low	1.0-1.3	Low	10-25
Moderate	1.3-1.6	Moderate	25-40
High	1.6-1.9	High	40-50
Very high	>1.9	Very high	>50

Sources: Hazelton and Murphy (2007)

Appendix Table 4: Rating of soil pH for 1:2.5 soils to water ratio suspension

pH	Rating
<4.5	Extremely acidic
4.5-5.0	Very strongly acidic
5.1-5.5	Strongly acidic
5.6-6.0	Moderately acidic
6.1-6.5	Slightly acidic
6.6-7.3	Neutral
7.4-7.8	Slightly alkaline
7.9-8.4	Moderately alkaline
>8.5	Strongly alkaline

Source: (Foth and Ellis, 1997)

Appendix Table 5: Ratings of soil organic matter, total nitrogen, CEC, AV.P and AWHC

SOM (%)	TN (%)	CEC(cmol(c)/kg)	AV.P(mg/kg)	AWHC (%)	Rating
-	-	>40	-	>21	Very high
>5.2	>0.25	25-40	>10	19-21	High
2.6-5.2	0.12-0.25	15-25	5-10	12-19	Medium
0.7-2.6	0.01-0.12	5-15	<10	8-12	Low
<0.7	<0.01	<5	-	<8	Very low

Sources: SOM (Berhanu, 1980), TN (Havlin, 1999), CEC (Landon, 1991), AV.P (Olsen *et al.*, 1954) and AWHC (Beernaert and Bitondo, 1990).

Appendix Table 6: Ratings of Exchangeable Basic Cations

Exchangeable Basic Cations (cmol(c)/kg)				
Ca	Mg	K	Na	Rating
<20	>8.0	>1.2	>2.0	Very High
10-20	3.0-8.0	0.6-1.2	0.7-2.0	High
5.0-10	0.1-3.0	0.3-0.6	0.3-0.7	Medium
2.0-5.0	0.3-1.0	0.2-0.3	0.1-0.3	Low
<2	<0.3	<0.2	<0.1	Very low

Source: (FAO, 2006)

Appendix Table 7: Ratings of Extractable Micronutrients

	Micronutrients (mg/kg)			
Rating	Cu	Fe	Zn	Mn
Very low	<0.2	0.1-0.6	<0.2	<0.2
Low	0.3-2.5	0.7-2.0	0.3-0.9	0.3-0.4
Medium	2.6-5.0	2.1-5.0	1.0-20	0.5-1.0
High	5.1-10	5.1-250	21-50	1.1-10
Very High	>10	>250	>50	>10

Source: (Jones, 2003)

Appendix Table 8: The ANOVA summary of chemical soil properties in Maya-Guddoo subwatershed

Soil Parameter	Sources of Variation	Df	SS	MS	F Value	P-value	Significance
pH (H_2O)	LULC Types	2	0.04	0.02	90.28	$4.14*10^{-10}$	HS(P<0.001)
	Slope Position	2	0.33	0.16	682.20	$< 2*10^{-16}$	HS(P<0.001)
	LULC*SP	4	0.98	0.25	1019.3	$< 2*10^{-16}$	HS(P<0.001)
	Residuals	18	0.004	0.0002			
EC (dS/m)	LULC Types	2	0.03	0.02	1551	$< 2*10^{-16}$	HS(P<0.001)
	Slope Position	2	0.03	0.02	1664	$< 2*10^{-16}$	HS(P<0.001)
	LULC*SP	4	0.05	0.01	1363	$< 2*10^{-16}$	HS(P<0.001)
	Residuals	18	$2*10^{-4}$	$1*10^{-5}$			
CEC (Cmol(c)/kg)	LULC Types	2	225.7	112.83	38.37	$3.23*10^{-7}$	HS(P<0.001)
	Slope Position	2	626.7	313.34	106.54	$1.06*10^{-10}$	HS(P<0.001)
	LULC*SP	4	594.5	148.62	50.53	$1.51*10^{-9}$	HS(P<0.001)
	Residuals	18	52.9	2.94			
AV.P (mg/kg)	LULC Types	2	828.5	414.2	245.10	$8.8*10^{-14}$	HS(P<0.001)
	Slope Position	2	154.4	77.2	45.66	$8.9*10^{-9}$	HS(P<0.001)
	LULC*SP	4	261.2	65.3	38.63	$1.3*10^{-8}$	HS(P<0.001)
	Residuals	18	30.4	1.7			
OC (%)	LULC Types	2	1.42	0.71	1583	$< 2*10^{-16}$	HS(P<0.001)
	Slope Position	2	1.52	0.76	1686	$< 2*10^{-16}$	HS(P<0.001)
	LULC*SP	4	4.00	1.00	2234	$< 2*10^{-16}$	HS(P<0.001)
	Residuals	18	0.008	0.0004			
OM (%)	LULC Types	2	4.21	2.11	1519	$< 2*10^{-16}$	HS(P<0.001)
	Slope Position	2	4.49	2.25	1619	$< 2*10^{-16}$	HS(P<0.001)
	LULC*SP	4	11.91	2.98	2147	$< 2*10^{-16}$	HS(P<0.001)
	Residuals	18	0.03	0.001			
TN (%)	LULC Types	2	0.005	0.003	6.80	0.006	S (P<0.05)
	Slope Position	2	0.002	0.001	2.33	0.13	NS
	LULC*SP	4	0.037	0.013	23.53	$6.1*10^{-7}$	HS(P<0.001)
	Residuals	18	0.007	0.0004			
C:N	LULC Types	2	101.6	50.79	33.43	$8.69*10^{-7}$	HS(P<0.001)
	Slope Position	2	173.9	86.94	57.23	$1.58*10^{-8}$	HS(P<0.001)
	LULC*SP	4	250.4	62.61	41.21	$7.91*10^{-9}$	HS(P<0.001)
	Residuals	18	27.35	1.52			

Appendix Table 9: ANOVA summary of Exchangeable Basic Cations and PBS in study area

Soil Parameter	Sources of Variation	Df	SS	MS	F Value	P-value	Significance
Na (cmol(c)/kg)	LULC Types	2	1.66	0.83	81.32	$9.7*10^{-10}$	HS(P<0.001)
	Slope Position	2	0.19	0.10	9.52	0.002	S (P<0.05)
	LULC*SP	4	0.88	0.22	21.69	$1.1*10^{-6}$	HS(P<0.001)
	Residuals	18	0.18	0.10			
K (cmol(c)/kg)	LULC Types	2	0.43	0.22	42.43	$1.5*10^{-7}$	HS(P<0.001)
	Slope Position	2	0.49	0.25	48.38	$5.8*10^{-8}$	HS(P<0.001)
	LULC*SP	4	0.61	0.15	30.13	$9.3*10^{-8}$	HS(P<0.001)
	Residuals	18	0.09	0.005			
Ca (cmol(c)/kg)	LULC Types	2	44.93	22.46	100.76	$1.68*10^{-10}$	HS(P<0.001)
	Slope Position	2	208.4	104.22	467.47	$3.06*10^{-16}$	HS(P<0.001)
	LULC*SP	4	82.51	20.63	92.53	$9.51*10^{-12}$	HS(P<0.001)
	Residuals	18	4.01	0.22			
Mg (cmol(c)/kg)	LULC Types	2	335.6	167.80	181.59	$1.17*10^{-12}$	HS(P<0.001)
	Slope Position	2	147.9	73.94	80.01	$1.10*10^{-9}$	HS(P<0.001)
	LULC*SP	4	359.6	89.91	97.29	$6.19*10^{-12}$	HS(P<0.001)
	Residuals	18	16.6	0.92			
PBS (%)	LULC Types	2	27.3	13.63	0.763	0.481	NS
	Slope Position	2	80.5	40.25	2.252	0.134	NS
	LULC*SP	4	47.1	11.78	0.659	0.628	NS
	Residuals	18	321.7	17.87			

Appendix Table 10: ANOVA summary of extractable micronutrients in study area

Soil Parameter	Sources of Variation	Df	SS	MS	F Value	P-value	Significance
Fe (mg/kg)	LULC Types	2	113.7	56.87	25.32	$5.86*10^{-6}$	HS(P<0.001)
	Slope Position	2	134.6	67.30	29.97	$1.87*10^{-6}$	HS(P<0.001)
	LULC*SP	4	398.9	99.72	44.40	$4.34*10^{-9}$	HS(P<0.001)
	Residuals	18	40.4	2.25			
Zn (mg/kg)	LULC Types	2	9.83	4.91	51.02	$3.83*10^{-8}$	HS(P<0.001)
	Slope Position	2	20.43	10.21	106.05	$1.10*10^{-10}$	HS(P<0.001)
	LULC*SP	4	2.09	0.52	5.42	0.0048	S(P<0.05)
	Residuals	18	1.73	0.096			
Cu (mg/kg)	LULC Types	2	17.98	8.99	107.47	$9.82*10^{-11}$	HS(P<0.001)
	Slope Position	2	25.52	12.76	152.52	$5.18*10^{-12}$	HS(P<0.001)
	LULC*SP	4	21.22	5.31	63.43	$2.31*10^{-10}$	HS(P<0.001)
	Residuals	18	1.51	0.08			
Mn (mg/kg)	LULC Types	2	146.4	73.21	54.36	$2.36*10^{-8}$	HS(P<0.001)
	Slope Position	2	128.9	64.45	47.85	$6.24*10^{-8}$	HS(P<0.001)
	LULC*SP	4	98.90	24.72	18.36	$3.66*10^{-6}$	HS(P<0.001)
	Residuals	18	24.24	1.35			

Appendix Table 11: ANOVA summary of soil quality index in Maya-Guddoo subwatershed

Soil Parameter	Sources of Variation	Df	SS	MS	F Value	P-value	Significance
SQI	LULC type	2	0.004	0.002	6.88	$6.03*10^{-3}$	S(P<0.05)
	Slope Position	2	0.032	0.016	58.36	$1.36*10^{-8}$	HS(P<0.001)
	LULC*SP	4	0.016	0.004	14.42	$1.91*10^{-5}$	HS(P<0.001)
	Residuals	18	0.005	0.0003			

Appendix Table 12: The ratings of soil quality index

SQ ratings	Scale	Classes
Very good	0.8-1.00	1
Good	0.6-0.79	2
Moderate	0.4-0.59	3
Low	0.2-0.39	4
Very Low	0.0-1.99	5

Source: (Cantu, 2007)