Addis Ababa University

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Soil Quality under Different Topo-sequences and Land Uses and Its Implication to Agriculture: the case of Choke Agroecosystem, Upper Blue Nile Basin, Ethiopia

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Declaration

I, the undersigned, declare that this is my original work, has never been presented at this or any other university, and that all the resources and materials used for the dissertation have been fully acknowledged.

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This Dissertation has been submitted for examination with my approval as the student's supervisor.

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Dissertation Approval

Addis Ababa University

College of Development Studies

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This is to certify that the Dissertation prepared by Demeku Mesfin, entitled " **Soil quality under different topo-sequences and land uses and its implication to agriculture: the case of Choke agroecosystem, upper Blue Nile Basin, Ethiopia.**" is presented in fulfillment of the requirements for the Degree of Doctor of Philosophy in Development Studies (Environment and Development Studies) and meets the accepted standards concerning originality and quality.

Signed by the Examining Committee:

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List of Original Papers

This Dissertation is organized based on the following four (4) original articles, where three of them published and one of them accepted with minor revision.

Paper 1. Mesfin, D., Assefa, E., & Simane, B. (2023). Characteristics of soil quality attributes under different agroecosystems and Its implications for agriculture in the Choke Mountain watershed in Ethiopia. *Frontiers of Agricultural Science and Engineering*, *2095–7505*, 1–11. https://doi.org/10.15302/J-FASE-2023502

Paper 2. Mesfin, D., Assefa, E., & Simane, B. (2022). Variability of soil quality indicators along with the different landscape positions of Choke Mountain agroecosystem, upper Blue Nile Basin, Ethiopia. *Heliyon*, *8*(7), e09850. https://doi.org/10.1016/j.heliyon.2022.e09850.

Paper 3. Mesfin, D., Assefa, E., & Simane, B. (2023). Soil Quality Index under Different Land Use Types: In the case of Choke Mountain Agroecosystems, Upper Blue Nile Basin, Ethiopia. *Canadian Journal of. Soil Science* 00: 1–12 (2023). https://doi.org/10.1139/cjss-2022-0053.

Paper 4. Mesfin, D., Assefa, E., Simane, B. (2023). Farmers and scientific-based assessment of soil quality in the Choke agroecosystem, Upper Blue Nile Basin, Ethiopia, *Environmental and Sustainability Indicators* (19), 100279. doi: https://doi.org/10.1016/j.indic.2023.100279.

Table of Content

Contents **Page**

List of Tables

List of Figure

Appendices

Abbreviations and Acronyms

AES	Agroecosystem
AES 1	Lowland and valley fragmented
AES 2	Midland plain dominated by black soil
AES 3	Midland plain with brown soil
AES 4	Sloppy midland land, and
AES 5	Hilly and mountainous highlands
ANOVA	Analysis of variance
Ava. P	Available phosphorous
BD	Bulk density
Ca	Exchangeable calcium;
CEC	Cation exchange capacity
CL	Cultivated land
Cm	Centimeter
CV	Coefficient of variation
CSA	Centeral statistical Agency
DEM	Digital Elevation Model
Ex. K	Exchangeable potassium
Ex. Na	Exchangeable sodium
GL	Grazing land
GIS	Geographic information system
Kg	Kilogram
KMO	Kaiser-Meyer-Olkin
NFL	Natural forest land

NGO	None governmental organization
MANOVA	Multivariate analysis of variance
M	Meter
MM	Millimeter;
MDS	Minimum data set
Mg	Exchangeable magnesium
OM	Organic matter
PBS	Percent base saturation
PCA	Principal component analysis
PFL	Plantation forest land
pH	Soil reaction
RF	Rainfall
SQ	Soil quality
SQI	Soil quality index
Temp	Temperature
TN	Total nitrogen
TP	Total porosity
UNEP	United Nations Environment Programme
UTM	Universal Transverse Mercator
WGS	World Geodetic System

Dedication

To my Mother for her struggle and commitment to fulfill the family's needs. She gives her life for us.

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Throughout the completion of my dissertation, I have gotten support from various individuals and organizations. I am pleased to take this chance to acknowledge my obligation to you. *Above all, I thank the Almighty God, who strengthened, protected, and led me through the years.*

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General Abstract

*Understanding the diversity of soil quality across topographic situations and various land uses is essential to enhancing land management mainly soil fertility, productivity, environmental sustainability, and sustainable agriculture. This study investigates soil quality under different topo-sequences, land uses, and its implication for agriculture: the Choke agroecosystem, upper Blue Nile Basin, Ethiopia. The data were collected from both soil and socioeconomic survey from the five agroecosystems (AESs), including lowland and valley fragmented (AES 1), midland plain dominated by black soil (AES 2), midland plain with brown soil (AES 3), sloppy midland land (AES 4), and hilly and mountainous highlands (AES 5) of the Choke watershed. Forty-seven composite soil samples were collected from 0-20 cm depth from the various topo-sequences (upper, middle, and lower) and different land use types (cultivated land - CL, grazing land - GL, plantation forest land - PFL, and natural forest land - NFL). Principal component analysis (PCA), analysis of variance (ANOVA), multivariate analysis of variance (MANOVA), and soil quality index (SQI) was used for the analysis of the soil quality. The result of the study revealed that, among the fifteen soil quality properties measured, ten, including silt, exchangeable bases, cation exchange capacity, percent base saturation, pH, organic matter, total nitrogen, and available phosphorous, were found statistically significant (P <05, P <.01) among the five AESs. But all measured soil quality properties vary within a range of coefficient of variation (CV%) from 7 (total Porosity) to 169 (available phosphorous) across the AESs. The interaction effect of AES and topo-sequence (AES*topo-sequence) substantially affects three soil quality indicators, including soil silt content, pH, and available phosphorus. AES had a significant impact on cation exchange capacity (CEC), and both AES and topography had a significant and distinct impact on organic matter (OM). The result of SQI for the general land uses was ordered as GL > NFL > PFL > CL. Compared with NFL, the SQI of PFL and CL were reduced by 10% and 19.7%, respectively, whereas the SQI of GL was increased by 1.8%. Among AESs of Choke, SQI of GL was higher in the midland plain, dominated by Vertisol (AES 2), followed by the midland plain with Nitosols (AES 3). SQI of CL was intermediate, and SQI of GL, NFL, and PFL was good. AES 2 of the watershed recorded the highest total SQI value, whereas hilly and mountainous highlands (AES 5) recorded the lowest SQI compared to other AESs. Simple descriptive statistics show a relationship between scientific soil quality assessments and indicators used by farmers to describe their farm fields. Farmers from the midland part of the watershed perceived a high soil quality with high crop yield with green leaf color, black/dark soil color with good water holding capacity. However, higher nutrients, including soil organic matter, total nitrogen, and available phosphorous recorded in the sloppy and mountainous highlands of the watershed. This shows that there is some inconsistency in the classification of soil quality of agricultural lands by farmers and scientific assessment across the various agroecosystems, which was created by the application of soil and crop management practice. Thus, the* *result suggested site-specific development of local knowledge on soil considering topo-sequences and land use type to improve agricultural productivity, land management practice and ease the constraints of each soil in each agroecosystem.*

Keywords*: *Soil quality indicators, topo-sequences, land use type, soil quality index, MANOVA, farmers' perception, agroecosystem, Choke watershed, Ethiopia

CHAPTER ONE

1. GENERAL INTRODUCTION

1.1 Background and Justification

The soil, a natural resource that is an integral part of the terrestrial ecosystem, is crucial for maintaining the primary plant nutrients (nitrogen, phosphorus, and potassium) (Elias et al., 2022). But as time passes, the foundation of this fundamentally significant natural capital deteriorates and becomes more susceptible to deterioration (Lal, 2015; Selassie et al., 2015) and manifests in land degradation. Lack of agricultural land due to fast population growth and the need for more food production strained the environment and accelerated land degradation (Teferi et al., 2016). Due to its effects on the environment and food security, land degradation has become of utmost concern globally (Bekele, 2019; Hurni et al., 2016).

Various factors contribute to land degradation, including deforestation, overgrazing, land use changes, and the expansion of agriculture into marginal lands. At the continent level, Africa is one of the most affected regions by land degradation, where the combination of natural factors and human activities has resulted in the deterioration of soil quality and a decline in agricultural productivity. As a result, soils are depleted of essential nutrients, eroded, and compacted, leading to a loss of soil structure and fertility (Tully et al., 2015).

According to UNEP (2021), over 65% of African land is affected by land degradation, leading to reduced crop yields, soil erosion, and biodiversity loss. The problem is particularly severe in sub-Saharan Africa, where most people rely on agriculture for their livelihoods. One of the key factors contributing to soil degradation in Africa is the overuse of land due to population growth and increasing demand for food. Farmers are often forced to cultivate marginal lands, which are unsuitable for agriculture, resulting in soil erosion and nutrient depletion. Moreover, the increasing use of fertilizers and pesticides has further degraded soil quality in some areas, leading to environmental contamination and soil acidification (Zingore et al., 2015).

Soil degradation – one component of land degradation has also long hindered Ethiopia's economy and people's well-being. According to estimates, soil deterioration costs the nation about 17% of its potential agricultural GDP (Hurni et al., 2016). For croplands, the average yearly soil loss rate is 42 tons ha^{-1}, with extreme situations reaching 300 tons ha^{-1} (Hurni, 1988). Soil erosion is one of the leading causes of soil degradation. In addition to natural factors, farming on steep and breakable soils, inadequate soil conservation investments, and decreasing fallow land usage are the leading causes of soil erosion and nutrient depletion (Assefa et al., 2020).

Despite these challenges, some African countries have taken steps to address the problem of land degradation and soil quality degradation (Mani et al., 2021). Ethiopia's government has acknowledged some of the country's traditional water and soil preservation practices. For instance, the Konso people long ago used terracing on their farmed land. Some terraces are also seen in the northern and lowland regions where water conservation is required. Other areas like Gojjam have developed systems of ditches to drain surplus runoff. However, these measures do not control soil erosion (Hurni et al., 2016). Soil and water conservation activities have been carried out by the Ministry of Agriculture in the past forty years on a large scale on cultivated land with contour (level) bunds, hillsides with afforestation terraces, and degraded hills with hillside closures. However, much more will be done in the future. Sustainable development can be achieved in rural areas of Ethiopia if farmers are supported at all levels – from policy to programs, from extension to NGOs, and international cooperation to private partnerships – in their efforts to conserve nature, use natural resources with afforestation wisely and engage in soil and water conservation. Since Ethiopia has a tremendous climatic variety, from dry to wet, and many different altitudes, from lowlands to highlands, the same conservation technologies cannot be applied everywhere (Hurni, 1998).

Soil erosion in the Choke watershed is also a well-recognized problem that local farmers identified as a priority problem affecting soil quality. Although traditional land management, including appropriate agricultural practices and sound forestry practices, has extensively protected the Choke from accelerated erosion in the past, today's land abandonment and forest mismanagement have dramatically increased the frequency of intensive soil erosion events. Steep slopes, traditional crisscross ox-drawn tillage systems that promote rapid erosion, and limited agricultural land use characterize the Choke environment (Simane et al., 2013). These activities deplete the main water tower of the watershed and biodiversity, leading to severe erosion (Simane et al., 2012). Besides, there is high population growth in the area, which leads to expanding marginal land cultivation of up to 3,800 masl and new human settlements of up to 3,600 masl in the Mountain area. This severity of soil erosion and the decline of its fertility have severe implications for agriculture, food security, and livelihoods of farming communities in the area.

Therefore, it is necessary to understand the characteristics of soil quality indicators in different landscape and land use types at an agroecosystem level where sustainable land management is to be implemented. However, there was a need to be more research on assessing soil quality under the different landscape and land use types considering agroecology in Ethiopia in general and an agroecosystems level in the Choke watershed in particular. That is why the current research was conducted in the agroecosystems of the Choke watershed in Ethiopia.

1.2 Literature Review

1.2.1 Soil quality: concept and definition

Soil quality refers to the soil function of sustaining plant and animal productivity, maintaining or enhancing water and air quality, and supporting human health and habitation (Karlen et al., 1997). The soil quality concept emerged in the early 1990s (Doran & Parkin, 1994), and the Soil Science Society of America first applied the term Ad Hoc Committee on Soil Quality (S-581) (Karlen et al., 1997). Soil quality provides a valuable and universal concept for educating professionals, producers, and the public about the importance of soils and offers an evaluation tool for appraising current management practices and comparing the advantages and disadvantages of alternative management practices (Zornoza et al., 2015).

The emerging soil quality concept also provided the focus for an international workshop entitled 'Assessment and Monitoring of Soil Quality' at the Rodale Institute Research Center in Emmaus, Pennsylvania. One result was a consensus that soil quality should incorporate environmental quality, human and animal health, and food safety and quality rather than just soil production (Karlen et al., 2003).

Soil quality became more prevalent in the vocabulary of policymakers, natural resource conservationists, scientists, and farmers after the US National Academy of Sciences published the book 'Soil and Water Quality: an Agenda for Agriculture' and specifically identified the need for more holistic soil quality research. Then soil quality was recognized and interpreted as a more sensitive and dynamic way to measure soil condition, response to management changes, and resilience to stresses imposed by natural forces or human uses (Bai et al., 2018; Yu et al., 2018a). It has biological, physical, and chemical properties, which are inherent and dynamic and can change due to some natural processes and in response to human use. The natural or inherent capacity of soil to support crops varies and depreciates with use. The depreciation rate also varies depending on the kind of use and the most affected soil properties (De La Rosa & Sobral, 2008; Olateju et al., 2015).

1.2.2 Soil quality and topography

Soil quality with topography refers to how the characteristics and properties of soil vary in relation to the physical features of the land or the topography of a particular area. Topography refers to the elevation, slope, and arrangement of landforms in a given landscape. Topography is an intrinsic factor in soil formation that also influences potential land use, though land use-land cover also has the potential to modify soil attributes, including soil organic matter and nutrient levels (Liu et al., 2020).

The topography of agricultural fields can influence soil physicochemical properties (soil depth, texture, and mineral contents), biomass production, incoming solar radiation, precipitation, and crop production. Soil texture is also an indicator of soil features vis-à-vis parent material types, homogeneity and heterogeneity within the profile, clay migration, and intensity of soil material weathering or soil age (Amuyou et al., 2013). As increased topography/elevation significantly increased soil moisture, precipitation, soil organic matter, and labile carbon, bulk density, pH, and soil temperature were significantly lower at the higher elevations (Amuyou et al., 2013).

Young, rolling soils are more affected by topography than older, level soils (Ziadat et al., 2010). Since topography is the inclination in percent degrees, length of slope in meters, and slope aspect, it results in microclimate and vegetation differences and, thus, soil differences and becomes the primary factor in explaining soil variation (Baskan et al., 2016). Slope and altitude attributes affect soil nutrient levels by influencing water budgets, soil erosion, deposition, and local drainage capacity (Baskan et al., 2016).

The soil of regions and sub-regions varies considerably due to various topographic, climatic, or agro-climatic conditions. Individual farmers have fragmented the land into small pieces causing wide variations in the management of every piece of land. This leads to a considerable variation in the indicators, even between adjacent plots. That is why generalizing soil characteristics is complex and underscores the need for more location-specific data on soil properties. For example, Nitrogen, phosphorus, and potassium balances also vary in the central highlands, with the highest nutrient depletion at foot slopes in Dega and the mid-slopes in Woina Dega (Haileslassie et al., 2006).

Ziadat et al. (2010) additionally highlight the presence of variability in soil quality indicators across various topographic units. For example, the clay content of the surface horizons of some soils that occur at the summit and shoulder positions was higher than the back slope and toe slope positions. Silt contents at the surface horizon, back slope, and toe slope positions were higher than those for the summit and shoulder positions. This is due to more migration of clay at lower slope members. Sand fraction for the summit and shoulder positions decreased with depth and was generally higher than at the back and toe slopes. On the contrary, Karaca et al. (2018) found no significant difference in soil nutrient contents, except boron, among the three topographic units (back slope, foot slope, and terrace).

1.2.3 Soil quality and land uses

Land use refers to the human activities and practices carried out on a particular piece of land. It would be beneficial to use appropriate land management practices like conservation agriculture which involves practices such as minimal soil disturbance, maintaining soil cover through crop residues or cover crops, and diversifying crop rotations. It helps to reduce soil erosion, improve water infiltration, enhance soil fertility, and promote long-term soil health. It helps to recover the deteriorated soil's physicochemical quality and assure steady and sustained productivity because land use and management practices are directly tied to soil quality (Panday et al., 2019). Unsustainable farming practices would negatively affect soil quality, showing that land use and land cover types play a typical role in soil quality (Delelegn et al., 2017; Kitila et al., 2018; Simane et al., 2013). In Ethiopia's highlands, converting forest to cultivated land may impact the soil's capacity to provide ecosystem services (Assefa et al., 2017).

Eucalyptus affects soil nutrients, soil erosion, climate, and the water cycle from an ecological standpoint (Amenu, 2017). Farmers in Ethiopia plant massive numbers of eucalyptus on small parcels of land and manage them to create a variety of goods and services. A study showed that the soil quality of plantation forests is significant for soil improvement. But when eucalyptus stands are harvested, much of the nutrients stored in the aboveground biomass are lost and affect soil fertility (Amenu, 2017; Mengistu et al., 2016). Large nutrient amounts are exported when Eucalyptus *spp*. plantation is harvested, causing a reduction in the soil nutrient content, such as total N and available P (Leite et al., 2010). Leite et al. (2010) reported that soil organic matter contents were higher in Eucalyptus *spp.* soils than in pasture areas due to the greater number of residues produced by the Eucalyptus *spp.* plantation that remained in the soil.

Although forest coverage has increased since 2018, a review of land use/cover change at the country level showed a continued decline in shrub and forest cover during 1980–2000 (Mengist, 2011). The expansion of cultivated land continued to very steep slopes and marginal lands that led to land degradation/ soil degradation problems in the highlands of Ethiopia (Simane et al., 2013). On the other hand, a land use change from pasture to sugarcane has induced slight improvements in soil quality, mainly driven by increasing soil chemical quality (Cherubin et al., 2016). Various studies show the status of soil quality among the different land use types across the globe (Bewket & Stroosnijder, 2003; Cherubin et al., 2016; Ghimire et al., 2018; Kalu et al., 2015; Negasa et al., 2017; Raiesi, 2017; Tesfahunegn, 2016; Yu et al., 2018b). Most researchers found that the cultivated land's soil quality was degraded because a substantial amount of soil organic matter was removed through harvesting.

Yu et al. (2018b) found that natural forest land soil quality is better than other land use types. However, the soil quality of agricultural land is greater than natural forest land following the finding of Jiang et al. (2020). Furthermore, intensive cultivation or continuous tillage system might also cause a quick decomposition rate.

1.2.4 Farmers and scientific view on soil quality

Farmers have shared specific regional knowledge and customs that give them a solid understanding of soil characteristics and effective management techniques (Dawoe et al., 2012; Mairura et al., 2007). This information mainly agrees with the area's scientific edaphic evaluation, yet a significant erosion-related gap has been found. Farmers are frequently aware of soil conservation issues and the potential for bettering soil management techniques. However, considerations of immediate expenses restrict their actual implementation. They had an ambivalent attitude toward agrarian institutions, which were viewed as having high expectations as sources of technical and financial support but also with some mistrust due to their regulatory and regulating duties (Barbero-Sierra et al., 2016).

To recognize such a global farmers' indigenous expertise, ethnopedology was created to record and comprehend regional perspectives on how soil is perceived, categorized, valued, used, and managed (Barrera-bassols & Zinck, 2003). Farmers have developed a local system of soil classification based on their experience of the potential and constraints of their soils. The soils are classified according to recognizable and identifiable soil and field characteristics (Corbeels, 2000). Following Bwambale's (2015) classification, farmers' soil quality indicators are based on crop performance, soil characteristics, and biological indicators. Farmers also use topographical indicators as a factor relating to the position of the field along the topo-sequence as a fourth indicator of soil quality, according to the findings of Dawoe et al. (2012) and Kuria et al. (2019a).

According to Mairura et al. (2007), organic matter, soil acidity, nitrogen, phosphorus, and potassium are the most critical factors influencing and manifesting crop growth characteristics related to the farmers' ability to recognize fields based on crop indicators. Farmers use soil color as a critical indicator to categorize soils worldwide (Corbeels, 2000; Dawoe et al., 2012; Wawire et al., 2021; Yageta et al., 2019). The color of the soil tails, the soil's organic content, and the profile's dark color could be attributed to a higher amount of soil organic matter, implying that darker soils were regarded to be more fertile (Wawire et al., 2021).

Furthermore, studies in Rwanda indicate that soil management practices depend on farmer's perception of site-specific land characteristics, such as plot position along the slope and land potential based on other inherent constraints, such as soil fertility status, soil texture, water availability, and crop diseases (Kuria et al., 2019b).

1.2.5 Conceptual framework of the study

Soil quality indicators are soil properties that can be measured, affecting how well the soil can produce crops and provide other ecosystem services. These properties include physical ones (such as bulk density, texture, aggregate stability, and porosity), chemical attributes (such as pH, cation exchange capacity, and nutrient levels), and biological ones (such as organic matter, organic carbon content, and microbial enzymes). Soil quality indicators can be divided into two types: inherent and dynamic. Inherent soil characteristics are determined by the factors that form the soil, such as climate, parent material, time, topography, and living organisms (JENNY, 1945). Dynamic soil quality indicators are affected by land use and management changes, such as cropping, grazing, or forestation.

Both natural and human-induced factors influence soil quality at the level of agroecosystems, which are combinations of agroecology, soil and terrain features, and farming strategies. When cultivated land expands at the expense of natural forest and grazing land, especially on steep slopes, soil erosion becomes a severe problem that degrades the soil's physical, chemical and biological quality (Lal, 2015). Topography, a factor that forms the soil, also affects soil quality indicators. Therefore, it is vital to understand how soil quality changes due to different land use and management practices and topographic conditions.

Furthermore, farmers' perceptions of soil quality are critical in determining their willingness to adopt sustainable land use practices. Farmers may have different perceptions of soil quality depending on their cultural, social, and economic contexts. Understanding farmers' perceptions of soil quality can help policymakers and researchers develop effective strategies to promote sustainable land use practices and improve soil quality.

In summary, soil quality indicators are essential for measuring and monitoring soil health, and inherent and dynamic soil properties play a significant role in determining soil quality. Topography and land use practices also affect soil quality, and farmers' perceptions of soil quality are essential in promoting sustainable land use practices. Farmers and land managers can maintain or improve soil quality, achieve economic sustainability, and protect the environment by adopting sustainable land use practices and implementing effective soil management strategies.

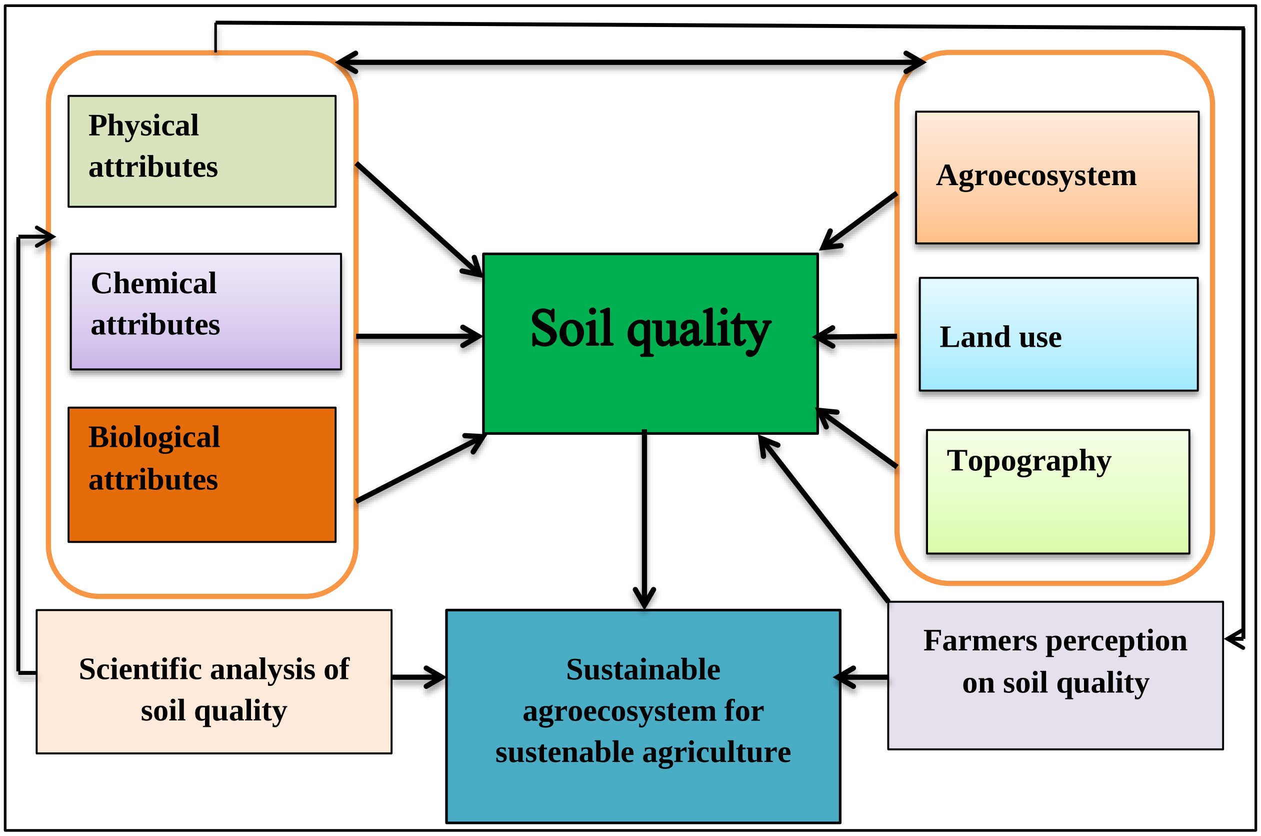

Figure 1.1 Conceptual framework of the study (Researcher's own construction)

1.3 Statement of the Problem

Land degradation is a significant immediate factor contributing to Ethiopia's low agricultural output, food insecurity, and rural poverty (Ewunetu et al., 2021; Teferi et al., 2016). Most highland parts of Ethiopia (including the upper parts of the Choke Mountain watershed) are among the most seriously affected by soil degradation- as one component of land degradation (Girmay & Singh, 2012; Hurni et al., 2016; Simane et al., 2013). Rural poverty and food insecurity in the Ethiopian smallholder farming system are due to soil degradation involving nutrient depletion (N, -122, P, -13 and K, -82 kg $ha^{-1}yr^{-1}$ –the highest in Sub-Saharan Africa). The negative soil nutrient balance shows the depleted fundamental soil nutrients (Elias et al., 2019) because of the limitation on sustainable management practices based on the soil system's understanding of scientists and farmers (Seifu et al., 2020).

Besides, physical land degradation (deterioration of soil structure, crusting, compaction, and erosion), chemical degradation (salinity, sodicity, acidity, soil fertility loss), and biological deterioration (loss of organic matter) are the leading indicator for the degradation of soil in Ethiopia (Seifu & Elias, 2018; Teferi et al., 2016). This degradation was driven by high population pressure, overgrazing, changes in land use, inappropriate agricultural practices, massive deforestation of natural forests, unwise agricultural expansion, and the rugged nature of the landscape are the major driver for soil degradation (Dagnachew et al., 2020; Gelaw et al., 2015; Seifu et al., 2020; Teferi et al., 2016). Factors aggravating soil degradation result in low soil fertility, lower yield, and higher environmental problems (Elias et al., 2022).

Understanding the spatial variability of soil quality concerning site characteristics, such as climate, land use, landscape position (topography), and other variables, is essential for estimating the consequences of potential future land use change on soil quality (Seifu et al., 2020). This indicates that the general status of soil qualities in a given landscape is mainly influenced by the land use system used in certain agroecosystems. Therefore, on a small watershed scale, topography and the forms of land use may be the primary determinants of the state of soil attributes (Mathewos, 2020), particularly in areas of multiple land use and farming systems and complex topography.

Topography is key in regulating soil and hydrological processes at the landscape scale. This influence may be seen in the soil catena concept (Seibert et al., 2007). The spatial variation of soil qualities substantially impacts environmental elements such as slope aspects caused by microclimate differences, terrain, parent materials, and vegetation communities (Yimer et al., 2006). Amuyou and Kotingo (2015) reported that slope positions and gradients significantly impact soil qualities, which are expressed in the distribution of soils. Plant development may be impacted by soil chemistry and moisture, and topographic features determine where plants are distributed in particular habitats (Seibert et al., 2007). Many authors (e.g., Amhakhian and Achimugu, 2002; Bufebo et al., 2021; Dessalegn et al., 2014; Rezaei et al., 2015) also reported the influence of topography on soil quality parameters.

In addition, changes in land use and its alterations on the ecosystem can significantly affect soil's physical, chemical, and biological properties (Bewket & Stroosnijder, 2003). Changes in the different land use types play a critical role in Ethiopia's increased rate of soil erosion. Cultivated lands showed a continuously increasing trend at the expense of forests and grasslands. Due to population growth, cultivable land is becoming less accessible, and soil erosion is developing alarmingly (Bekele, 2019). Sheleme (2017) reported that the content of exchangeable bases, such as OC and CEC, was higher in grasslands in southern Ethiopia than in cultivated soils. The shift from forest to cultivation decreased OM, accessible phosphorus, and porosity; however, an analysis of the BD and pH trends revealed an opposite tendency (Seifu & Elias, 2018). Compared to forestland and pasture grounds, cultivated land has more acidic soils (pH < 5.4)(Assefa et al., 2020).

Studies from various parts of the globe (Dawoe et al., 2012; Kuria et al., 2019; Mairura et al., 2007; Wawire et al., 2021; Yirgalem, 2015) also show that declining soil quality in their cultivated land is perceived by most farmers and considered as a major constraint to agricultural production. Thus, understanding farmers' perception of soil related to objective soil properties is vital to using knowledge as a resource in the scientific investigation of soil (Gruver & Weil, 2007). Both farmers and scientists have used various techniques to evaluate soil using qualitative and quantitative indices (Laekemariam et al., 2017). Their expertise can provide a wealth of information for sustainable soil management in their specific farm plots at a specific agroecosystem ranging from a valley gorge to hilly and mountainous parts.

Accordingly, assessing the soil quality status scientifically and farmers' knowledge of the different topo-sequence and land use types is fundamental and essential in land management decision-making, climate change mitigation, landscape planning, and sustainable crop production (Miheretu & Yimer, 2018). Various studies were conducted elsewhere to assess the variability of soil quality under the different topo-sequence and land use types (Asadi et al., 2012; Dessalegn et al., 2014; Jendoubi et al., 2019; Karaca et al., 2018; Liu et al., 2017; Negasa et al., 2017; Pham et al., 2018; Seifu et al., 2020; Wang et al., 2001). However, studies did not compare scientific results with farmers' perceptions of soil quality in the study area. Furthermore, the studies do not consider the various agroecosystems, which is the primary concern of this study. The Choke watershed extends from tropical alpine environments at over 4,000 masl to the hot and dry Blue Nile gorge, including areas below 1,000 masl and containing diverse slope forms and soil types. But these broad agroecosystems lack detailed data and information on land use, and topography effects on soil quality and local knowledge on soil are few in the watershed under consideration.

There is, therefore, a need to study the soil quality of the agroecosystems with specific landscape and land use types for sustainable land resource management and to boost watershed-level crop productivity in the agroecosystems of Choke watershed in Ethiopia.

1.4 Research Questions

The study focuses on addressing the following questions generated from the specific objectives:

1. How do soil quality indicators vary across the different agroecosystems of the Choke watershed?
2. What is the effect of the agroecosystem, landscape position, and their combination on soil quality indicators in the Choke Mountain watershed?
3. Does the soil quality index vary among different land uses of agroecosystems in the Choke watershed?
4. How do farmers perceive and understand the soil of their farmland in the study area?

1.5 Objectives of the Study

1.5.1 General objectives

The major objective of the study is assess the soil quality of topo-unites and land uses and comparing with farmers' perception of soil quality in the agroecosystems of Choke watershed, upper Blue Nile Basin, Ethiopia.

1.5.2 Specific objectives

Specifically, the study aimed to:

1. Characterize soil quality attributes under different agroecosystems and its implications for agriculture
2. Analyze the variability of soil quality indicators along the different landscape positions of the Choke agroecosystem
3. Establish the soil quality index of Choke's different land use types and agroecosystems
4. Evaluate farmers' and scientific-based soil quality assessment in the study area

1.6 General Materials and Methods

1.6.1 The study area

Ethiopia is located in the Horn of Africa. Ethiopia has a high central plateau, the Abyssinian Highlands (or Ethiopian Highlands), that varies from 1,290 to 3,000 masl, with some 25 Mountains whose peaks rise over 4,000 masl, the highest being Ras Dashen at 4,543 masl (https://ethiopianembassy.org/overview-about-ethiopia/) followed by Choke Mountain, Upper Blue Nile Basin (4,200 masl).

The study was undertaken in Choke Mountain in the East Gojjam zone, a vast block of highland North Western Ethiopia, Amhara Regional state. It is on plateaus rising from a block of meadows and valleys at an elevation of 800 to 4,200 masl elevation. The central peak can be found at 10^{o} 10' to 11^{o} 30' N latitude and 36^{o} 50' to 38^{o} 30' E (Fig 1.2). While the central cone of the Mountain chains of Choke occurs in six woredas of East Gojjam, namely Hulet Eju Enesie, Enarj Enawga, Sinan, Debay Telatgin, Bibugn and Machakel, the Mountain watershed includes all East Gojjam and part of West Gojjam. Choke Mountain is a known bio-diversity-rich hotspot area found South of Lake Tana in the Amhara Region, east Gojam Zone. It is a water tower of the upper Blue Nile Basin and a source of over 60 rivers and 270 springs.

The watershed has six different agroecosystem zones (overlaying agroecology, soil, and farming systems) (Simane et al., 2013) with various bio-diversity and the source of many tributaries to the Nile. Most of it is covered by Mountains and gorges, the source of river waters that are mostly tributary to the Blue Nile. These are:- lowland and valley fragmented (AES 1); midland plains dominated by Vertisols (AES 2); midland plains having Nitosols (AES 3); midland sloping lands (AES 4); hilly and mountainous highlands (AES 5), and Afro-Alpine (AES 6).

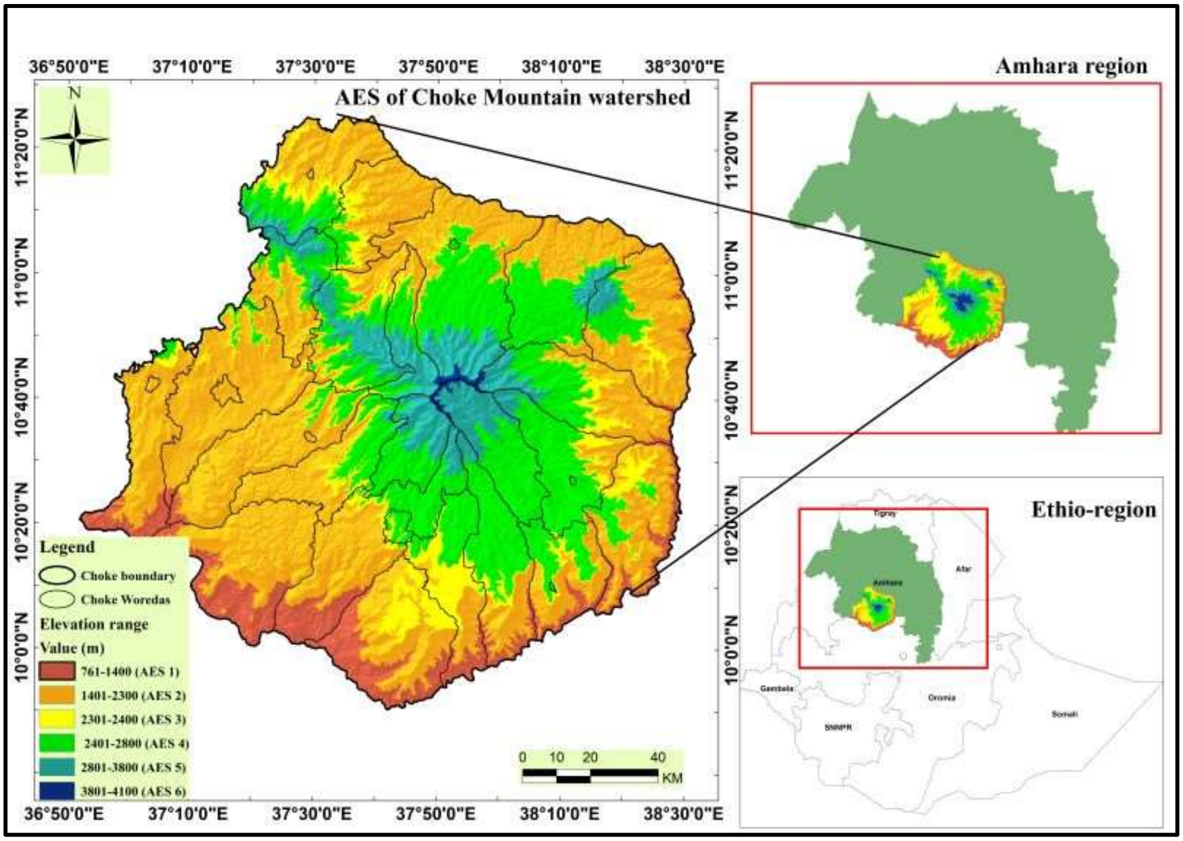

Figure 1.2 Map of the study area, AES of Choke Mountain watershed, upper Blue Nile, Ethiopia

Note: AES 1, lowland and valley fragmented; AES 2, midland plain dominated by vertisol; AES 3, midland plain dominated by Nitosols; AES 4, sloppy midland land; AES 5, hilly and mountainous highlands; AES 6, Afro-Alpine

Climate and Soil: The research area features a typical tropical monsoon climate with two seasons: *Bega*[1] from October to May and *Kiremt*[2] from June to September. Rainfall variation affects agricultural production, hydrological processes, and soil erosion rates. Rainfall distribution across the Blue Nile highlands shows variability associated with topographic gradients. The most substantial precipitation gradients in the study sites follow elevation: the wettest conditions are at high elevation, and the driest states are in the Blue Nile gorge. Rainfall is not evenly distributed, ranging from 600 to 2,000 mm year^{-1}, and varies locally because of topographic gradients. The mean monthly temperature of the agroecosystems ranges from 7.5^{o}C (hilly and mountainous part of the Choke) to 27.5^{o}C (Abay gorge). These precipitation contrasts, combined with the elevation of the temperature gradient, produce a sequence of distinct

[1] Dry season in Ethiopia
[2] Rainy season in Ethiopia

agroecological zones. Different ecologies, soil types, and crop mixes characterize the agroecosystems of the Choke watershed (Table 1.1).

The Choke Mountain (headwaters of the Blue Nile) is characterized by long steep slopes intensively used for agriculture and forestry, high-intensity rainfall and significant direct runoff generation and erosion, high ecological degradation, a high and steadily increasing population pressure, and vulnerability to climate change. Each Choke watershed agroecosystem has been characterized by different soil types based on FAO's soil classification. Lowland and valley fragmented (AES 1) is dominated by Leptosols and Cambisols; midland plains are dominated by Vertisols (AES 2); midland plains have Nitosols and Alisols (AES 3); midland sloping lands (AES 4) with Leptosols, Nitosols, and Alisols; hilly and mountainous highlands (AES 5) dominated by Leptosols and Luvisols, and the summit part of the watershed, Afro-Alpine (AES 6) is dominated by Cambisols, Andosols, and Phaozems (Simane et al., 2013). AES 6 is an Afro-Alpine on the Choke Mountain top, with elevations ranging from 3,800 to 4,200 masl; it is a protected bio-reserve and is not part of the current study (Table 1.1).

Table 1.1 Characteristic of study agroecosystems of Choke watershed

Agroecosystems (AES)	Farming systems	Mean annual RF (mm)	Mean annual temp (^oC)	Elevation Ranges (m)	Major soils	Major crops
Lowland and valley fragmented (AES 1)	Fragmented sorghum-based, extensive	< 900	21-27.5	800-1400	Leptosols Cambisols	Sorghum (*Sorghum bicolor*), tef (*Eragrostis abyssinica*) Maize (*Zea mays*), haricot bean (*Phaseolus vulgaris)*
Midland plain with black soil (AES 2)	Intensive teff-based	900-1200	11-15	1400-2300	Vertisols	Tef (*Eragrostis abyssinica*), durum wheat (*Triticum durum*), barley (*Hordeum vulgare*), chickpea (*Cicer arietinum*),
Midland plain with brown soil (AES 3)	Intensive Maize-Wheat based	900-1200	16-21	1400-2400	Nitosols Alisols	Maize (*Zea mays*), Wheat (*Triticum spp.*), Tef (*Eragrostis abyssinica*)
Midland slopping lands (AES 4)	Semi-intensive Wheat/barley-based	1200-1400	11-15	2400-2800	Leptosols Nitosols Alisols	Wheat *(Triticum spp.)*, tef (*Eragrostis abyssinica*), barley (*Hordeum vulgare*), engido (*Avena spp.*)
Hilly and mountainous highlands (AES 5)	Barley/potato-based	≥ 1400	7.5-10	2800-3800	Leptosols Luvisols	Barley (*Hordeum vulgare*), potato (*Solamum tuberosum*), Fava bean (*Vicia fava), engido (Avena spp.)*

Note: RF, rainfall; temp, temperature; ^oC, degree centigrade; mm, millimeter; m, meter

Agriculture: The Choke Mountain watersheds have various types of farming, but most of them are crop-livestock mixed systems. Smallholder farmers do these on plots of about 0.5 hectares. They grow crops like tef, maize, wheat, barley, and potatoes for their own use or for selling in the local or regional markets (Simane et al., 2013). They also keep animals like horses, sheep, cows, and oxen. A common feature of the cropping patterns in the Ethiopian Highlands is the traditional Ethiopian ard (or maresha) plough. This simple wooden plough pulled by oxen can break through hard and dry topsoils. These soils are typical of tropical volcanic areas. However, this plough also causes a lot of soil erosion on steep slopes and creates a hard layer that prevents water from infiltrating the soil. Other factors that contribute to soil erosion and loss of soil fertility in the Choke Mountain watersheds are overgrazing and deforestation. There is also a high demand for animal feed and firewood that puts pressure on natural resources.

The watershed faces severe threats from uncontrolled agriculture, overgrazing, rural settlements, and climate variability. Agriculture and settlements have expanded to high altitudes above 3,800 meters above sea level (masl), and grasslands have reached near the top of Mount Choke at 4,000 masl. Until recently, these areas had untouched forests and grasslands only used for grazing, collecting fuel wood, and sometimes growing barley or potatoes. This changed in the 1980s because of population pressure. Similarly, the lowest altitude zone (AES 1) is the steep and rugged terrain of the gorge that had good scrub and tree cover until recently. People also invaded these woodlands as the population increased.

1.6.2 Research design

This study applied a cross-sectional research design because it obtained both soil and socioeconomic data in one field visit. This design was selected because it is adaptable, economical, and allows for concurrent data access from plot farm household surveys and soil sample collection. The study employed a mixed (qualitative and quantitative) approach with a concurrent triangulation technique; hence, the data forms are both qualitative and quantitative. This approach is favored over others because it can back up, cross-check or verify the findings within a single study (either qualitative or quantitative).

Furthermore, this approach allows the researcher to collect data fast (Aalberg et al., 2012). However, more weight was given to the quantitative approach because of the nature of this study. The qualitative data was primarily used to supplement and triangulate the quantitative data to draw reliable conclusions.

1.6.3 Type and source of data

Both primary and secondary sources were employed using multiple interdisciplinary methods and approaches to collect socio-economic and soil data.

Primary sources were obtained from the soil survey, household survey, key informant interview, and direct observation.

Secondary sources were collected from the internet (Satellite Data) and related literature, such as journal articles, books, reports, and guidelines. Satellite data was used to select the field site in the study area. In the watershed, methods were used to choose the representative sites for investigation. Choke Mountain watershed was already divided into six AES and had an elevation range of about 800 – 4,200 masl. On each AES, transects were established, and the dominant topo-units were marked on the map using Digital Elevation Model (DEM) that was freely downloaded from Shuttle Radar Topographic Mission. The topo-units were classified as upper, middle, and lower (paper II). Likewise, land use types were identified from each agroecosystem (paper III) to collect soil samples and conduct farm plot surveys (paper IV).

1.6.4 Data collection methods

This study used various tools to enhance the reliability of each data collection tool and obtain comprehensive data. Specifically, the soil and socio-economic data were collected using soil sampling, household surveys, key informant interviews, field observation, and secondary sources.

Soil sample and sampling strategy

The soil test for this research and others was done in Ethiopia during the dry season (January 2021). First, dry-state soil sampling makes it easier to dig and handle the soil, reduces the risk of soil compaction or settlement errors, and ensures that all samples are taken under similar conditions for more reliable comparisons (Ackerson, n.d.). It also helps to avoid sample contamination due to lower microbial activity and helps to preserve soil structure during transport and storage. Secondly, field crops are usually harvested before January in the study area. Thirdly, crossing for observing and sampling soils becomes easier during this dry season than during wet, muddy, and sticky times. The soil samples were taken from the agroecosystems of the area, considering topo-unites and land uses. Using an auger, this was done by taking composite samples from the surface soil (0–20 cm) of a 10 m by 10 m square plot. A total of 47 soil samples were taken from five points (the four corners and the center of the plot). The representativeness of the samples was determined by the sampling strategy and homogeneity/heterogeneity of the area. Systematic sampling strategy was employed to collect soil samples, which helps to reduce biased and ensure representativeness of the samples.

The current study uses a consistent soil sample depth of 0-20 cm for all topo-sequences and land use categories after carefully considering some critical factors. The top 20 cm of soil is generally recognized as a fundamental layer for soil studies (Yost & Hartemink, 2020) because it has a high concentration of soil nutrients and is sensitive to topography and land use change. Also, consistent soil sampling depth simplifies the collection process and standardizes the methodology. Undisturbed core samples were also collected from each sampled agroecosystem in the middle of the selected plot using a cylindrical metal core sampler. The soil samples were placed correctly in plastic bags with proper labeling in each sample and taken to the national soil testing center for laboratory analysis. Undisturbed soil samples were collected using a core sampler to measure bulk density (Sahlemedhin and Taye, 2000) at the soil laboratory center of Addis Ababa University, Ethiopia.

Household survey

Between December 2020 and January 2021, social survey data with pre-tested semi-structured questionnaires from 123 farmers selected purposefully from five agroecosystems (AES 1, AES 2, AES 3, AES 4, and AES 5) was gathered. The majority of the chosen farmers were farmers engaged in agricultural pursuits. The selection criteria were based on the people's main economic activity, which in this case was agriculture. To gather information on soil quality and on the status, indicators, and classification of soil quality based on indicators, pre-tested structured and semi-structured questionnaires were utilized in the survey. Crop performance, soil properties, biological indicators, and topographic factors were requested to categorize soil quality as high, medium, or low based on predetermined indications from the literature review (Appendix 1).

Key informant interview

Key informant interview was used to gather qualitative information. This instrument provides in-depth information about the status and trends of soil quality and the major problems, including soil erosion, soil compaction, and soil nutrient depletion. Furthermore, the indicators that they used to classify their soil quality as high, medium, and low were asked. The key informants of this study were the elderly people who lived for long years in the study area and filled their soil quality change and expertise in natural resources management and crop production in each selected site. For these purposes, a total of ten (two from each agroecosystem) key informant interviews were conducted. The researcher employed the interview using the checklist (Appendix 2).

Field observation

Field observation was applied to see some of the observable evidence of the study. This enables us to observe the actual situation and current biophysical status of the soil/land resources. Likewise, it enables the identification of various topography, land use types, and soil colors across the agroecosystems. The observation data were recorded in photos and text to supplement results from other data sources.

Figure 1.3 Observation at AES 5, AES 2, and AES 4, respectively (2021)

1.6.5 Soil lab analysis

The samples were air-dried, crushed, and ground using a pestle and mortar and passed through a 2 mm sieve, except for SOC and TN. A 0.5 mm sieve mesh was needed to prepare organic carbon and nitrogen (Sahlemedhin and Taye, 2000).

After preparing the soil, the sample was analyzed following the standard soil analytical procedures. Soil particle size distribution was determined by the Bouyoucos hydrometric method (Bouyoucos, 1962). Whereas the BD of the soil was analyzed following the formula:

$$BD = oven\_dry\ weight\ of\ soil/volume\ of\ soil$$

The total porosity of the soil was determined as follows:

$$P = (1 - BD)/d) \times 100$$

Where *P* is total porosity (%), *BD* is the bulk density, and *d* is the particle density equal to 2.65 g cm^{-3} (Landon, 1991).

Soil pH was measured in a 1:2.5 soil to water suspension following the procedure outlined by Sahlemedhin and Taye (2000). The total nitrogen content was determined using the Kjeldahl method (Jackson, 1958) by oxidizing soil samples with sulfuric acid and converting the N compounds into $NH4^+$ as ammonium sulfate. The Walkley & Black (1934) wet digestion method was used to determine soil carbon content, and the percent SOM was calculated by multiplying the percent soil organic carbon by a factor of 1.724. Phosphorus was measured according to the standard procedure of the Olsen et al. (1954) extraction method and measured by a spectrophotometer. The ammonium acetate technique determined the CEC and exchangeable bases (Black, 1965). The exchangeable Ca and Mg from the extract were calculated using an atomic absorption spectrophotometer. The exchangeable K and Na were determined using a flame photometer from similar entities. Divide the sum of base cations by the cation exchange capacity multiplied by 100 to get the proportion of percent base saturation (Landon, 1991).

1.6.6 Method of data analysis

The data analysis involved both descriptive and inferential statistics. The qualitative data from key informants and observation supplemented, validated, and enriched the quantitative data from soil and household surveys. The qualitative data also provided information about the study area from secondary sources. The household survey data were analyzed descriptively using frequency, mean, standard deviation, and percentage. These methods revealed the socioeconomic and demographic characteristics of the farm households and compared their perception of soil quality with the scientific analysis.

The inferential statistics used in this study included analysis of variance, multivariate analysis of variance, Chi-square test and correlation analysis. These methods examined the relationship and variability of soil quality indicators (dependent variables) across the watershed, topographic units, and land uses (independent variables). Additionally, satellite images were analyzed using ArcGIS 10.5 software.

1.6.7 General flow chart of the study

Different datasets, data analysis techniques, and software were used in the study to accomplish the specific goals and respond to the fundamental research question. Figure 1.4 displays the study's overall process.

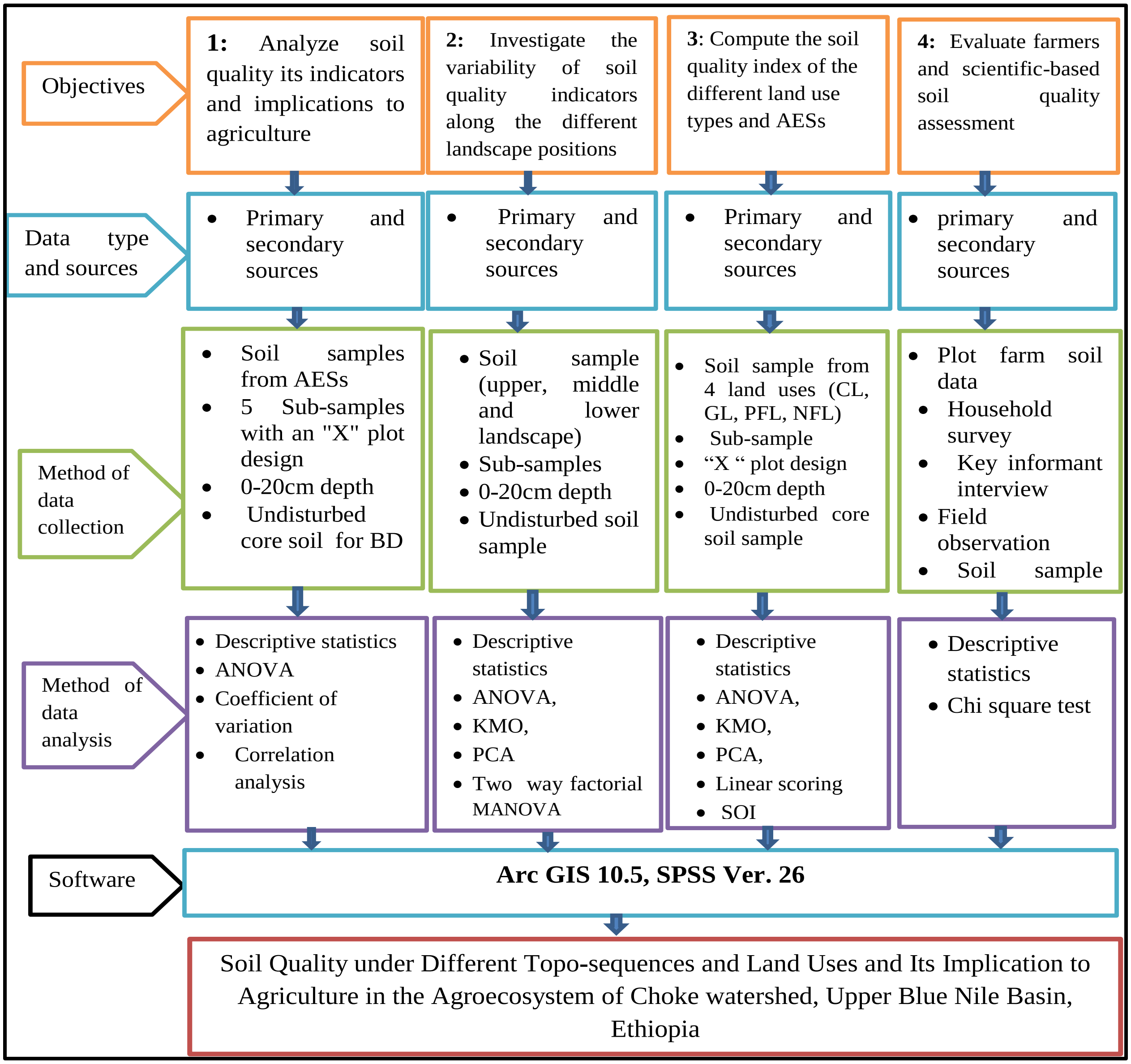

Figure 1.4 General flow chart of the study

1.7 Overview of the Dissertation

This section provides an overview of a Ph.D. dissertation, summarizing the original contributions to the literature and how the chapters link together.

The first chapter presents an introductory part containing the background and justification of why the study area selected, defining the issue of soil quality and its linkage with topography, land uses, and farmers' views on soil quality was also reviewed under this chapter. The framework of the study followed from the literature that shows the dependent and independent variables of the study, the problem statement with the gap and the scope of the study explained here in the introduction part of the study. Finally, both the general and specific objectives were identified, followed by the general methodology of the study applied to each objective.

Chapter two describes the characteristics of physical and bio-chemical soil quality indicators in agroecosystems of the Choke watershed and considers which indicators vary greatly and the cause for the variability of indicators among the five agroecosystems. The study also considers the correlation of indicators and the implication of soil quality indicators for agriculture. The indicators varied from low (total porosity) to very high coefficient of variation (available phosphorous). The study agroecosystems were dominated by clayey texture, indicating the similarities of the parent material. The study's steep slope and the mountainous highland area were affected by nutrient leaching caused by high rainfall and contributed to acidic soil. The midland area of the study was suitable for agriculture but dominated by low organic matter due to waterlogging problems. Since chapter two identifies the overall variability of soil quality indicators in each agroecosystem, chapter three explicitly identifies the effect of both landscape and agroecosystem's main and interaction effects on the selected soil quality indicators using MANOVA. The study found that the interaction effect of landscape and AES (landscape*AES) affects three soil quality indicators including silt content, pH, and available P. The main effect of landscape and AES also affects CEC and organic matter (OM). The result indicates the site-specific analysis of the soil to identify the specific characteristics of soil quality indicators in each AES, including land use types, which were identified in chapter four.

Thus, the soil quality index of the land uses (cultivated land, grazing land, eucalyptus plantation forest land, and natural forest land) in each AES of the Choke watershed was calculated by integrating physical, chemical, and biological indicators of soil quality. The integrated soil quality index (SQI) revealed grazing land of the watershed recorded the highest (0.74) index, followed by the natural land use. Cultivated land was under the intermediate (0.58) class of SQI, attributed to the removal of crop residue from the land and the low content of OM. Land use change from natural forest to land grazing land increase SQI by 1.8%, while from natural forest land to cultivated land and plantation forest decreased the value of SQI by 19.7% and 9%, respectively. Among the AES, in the midland plain area dominated by Vertisols, SQI was good and those with steep slopes and mountainous parts of the watershed records were relatively low.

Since observing soil quality from one direction (scientific analysis) does not sustain soil management in an agroecosystem, Chapter five compares results from scientific analysis with farmer’s perception of soil in each agroecosystem. Farmers view their soil from their experience with the performance of crop and soil characteristics, including the color and workability of the soil. The results showed similar except regarding the soil color, where black soil was found in AES 2 of the watershed but with a low organic matter content.

Finally, the sixth chapter synthesizes the study's main findings, contribution to literature, policy maker, and conclusion with a future area direction.

CHAPTER TWO

2. CHARACTERISTICS OF SOIL QUALITY ATTRIBUTES UNDER DIFFERENT AGROECOSYSTEMS AND ITS IMPLICATIONS FOR AGRICULTURE IN THE CHOKE MOUNTAIN WATERSHED IN ETHIOPIA

Abstract

Awareness of how soil properties vary over agroecosystems (AES) is essential for understanding soil potentials and improving site-specific agricultural management strategies for a sustainable ecosystem. This study examined the characteristics of soil quality attributes and implications for agriculture in the Choke Mountain watershed in Ethiopia. Forty-seven composite soil samples (0-20 cm deep) were collected from lowland and valley fragmented (AES 1), midland plain dominated by black soil (AES 2), midland plain with brown soil (AES 3), sloppy midland land (AES 4), and hilly and mountainous highlands (AES 5). Ten of fifteen soil quality properties were significant ($P < 0.05$ or 0.01), including silt, exchangeable bases, cation exchange capacity, percent base saturation, pH, organic matter, total nitrogen, and available phosphorous across the five AES. However, all properties were variable, with coefficients of variation from 7% (total porosity) to 169% (available phosphorous) across the AES. Although AES 2 and 3 are affected by waterlogging and acidity, these two have better prospects for agriculture, but AES 1, 4, and 5 are unsuitable for agriculture because of soil erosion. Therefore, appropriate and applicable soil management strategies, particularly lime application and organic fertilizer, are fundamental to reversing soil acidity and improving soil fertility.

Keywords: *Agroecosystem, coefficient of variation, soil quality properties, Choke Mountain watershed, Ethiopia*

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2.1 Introduction

Soil quality degradation occurs worldwide through adverse effects on soil's physical, chemical, and biological properties and inorganic and organic contamination caused by human activities (Arshad & Martin, 2002; Sánchez-Navarro et al., 2015). Ensuring soil quality at an acceptable level is challenging due to the interaction of climate, soil, plant, and human factors (Seevagan et al., 2020). However, by adopting specific soil, crop, and plant management practices, it is possible to reduce soil degradation or maintain soil quality at desirable or threshold levels to increase crop products (Fageria, 2002).

Reducing or/and avoiding soil degradation and improving soil health and fertility level could be achieved by performing sustainable soil management with an appropriate understanding of soil properties variability (Zhao et al., 2013). Soil properties' spatial variability is caused by farming management practices, such as irrigation and fertilization, and soil formation factors, like soil parent materials, climate, and vegetation (Al Alwani & Al-Shaye, 2019; Elias et al., 2022; Goenster-Jordan et al., 2018).

Ethiopia's tremendous climatic variety, which ranges from dry to wet, various altitudes, lowlands to highlands, and mixed farming systems caused soil variability among the different agro-ecological zones (Hurni et al., 2016). The highland areas received a high amount of rainfall, which caused the leaching of essential soil nutrients (basically soluble salts) and reduced agricultural production, whereas the rugged terrain feature plays a significant role in soil weathering processes through its influence on erosion, water movement, drainage patterns, and microclimatic conditions (Teshome et al., 2020). This shows that soil properties vary in different spatial areas because of the combined effect of natural and anthropogenic factors. However, deforestation, excessive grazing, and inappropriate farming methods were the main human-induced causes that exacerbated soil variability and led to a remarkable decline in soil organic matter (Abegaz et al., 2016; Ebabu et al., 2020; Gelaw et al., 2015). The highland regions of Ethiopia, where 87% of the nation's population lives, and poor farming practices have been used for centuries, were particularly affected by these damaging activities (Hurni et al., 2016).

Choke Mountain watershed is among the Ethiopian highland areas, characterized by steep slopes, intensively used for agriculture and forestry, high-intensity rainfall, significant direct runoff generation, and soil erosion. Given that nutrients in Choke soils tend to be concentrated in the upper region of the soil column, high rates of on-field erosion pose a particular concern (Simane et al., 2012), which creates variability of soil properties in different agroecological zones.

Studies were conducted elsewhere regarding the variability of soil properties that might be attributed to altitude, the intensity of tillage, the cropping system with the management system, and others. For example, Goenster-Jordan et al. (2018) show the wide variability of soil properties within a short distance because of the above factors. Al Alwani and Al-Shaye (2019), who conducted research in Iraq, found that climate variability and management practices could cause the variability of soil reactions from one place to another. Exchangeable bases are distributed differently depending on the particle size distribution, degree of weathering, soil management techniques, and level of cultivation, as reported by Negasa et al. (2017). Abate and Kibret (2016) also show that altitude, tillage intensity, agricultural method, and soil management strategies could be the most likely causes of soil organic matter concentration variation among the land units.

Furthermore, Bewket and Stroosnijder (2003), Ebabu et al. (2020), and Teferi et al. (2016) conducted on the effects of land use types on selected soil properties at one or two of the agroecological zone of the Choke watershed. The Choke watershed extends from tropical alpine environments at over 4,000 masl to the hot and dry Blue Nile gorge, including areas below 1,000 masl and containing diverse slope forms and soil types. However, the above studies did not incorporate the broad agroecosystems of the watershed, which is the main concern of this study.

Therefore, to fill such a gap, the study assessed soil quality characteristics and its implication for agriculture among the AES of the Choke watershed in the upper Blue Nile Basin of Ethiopia. The results from research-based knowledge and experimental data on soil's physical and bio-chemical properties are expected to provide accurate information on the status and variability of soil nutrients at an AES level to develop future practical and sustainable soil management strategies for sustainable agriculture.

2.2 Materials and Methods

2.1.1 Soil samplings and analysis procedures

Before collecting soil samples, a reconnaissance survey was conducted with the *Woreda's*[3] development agents in each agroecosystem. Soil sampling locations were then selected to take a representative soil sample from each agroecosystem of the watershed, which was considered a variation in the agroclimatic zone, farming system, and soil and terrain attributes. From the study area, surface soil samples (0-20 cm deep) were collected in January 2021 using a soil auger from five AES (Table 1) of the Choke Mountain watershed. Forty-seven samples of the soil were collected; 5, 9, 9, 12, and 12 samples from AES 1 to 5, respectively. Five subsamples were collected and mixed well at each sampling site, and only 1 kg of the composite soil sample was kept for analysis. Using steel cylinder (6 cm x 6 cm) with a sharp edge was used to collect undisturbed soil cores at each site for bulk density (BD) determination after drying the cores at 105°C (Sahlemedhin and Taye, 2000) with BD calculated as dry soil weight per unit volume.

2.1.2 Statistical analysis

The Shapiro-Wilk test was applied to see the distribution of the normality of variables. A logarithmic transformation was applied used to normalize non-normally distributed data. The measured soil data were subjected to statistical analysis using Microsoft Excel and SPSS (Ver.26). Properties of soil quality in the samples were analyzed using descriptive statistics (means, standard deviations, and standard error), and variability among agroecosystem was assessed using a coefficient of variation (CV%). Based on Phil-Eze's (2010) classification, CV within a range of < 20%, 20-50%, 50-100%, and >100% were regarded as low, moderate, high, and very high variability. A one-way analysis of variance (ANOVA) was performed on the data to compare the average values of the soil quality attributes across the AES. The mean comparison was conducted using the least significant difference (LSD) test at $p < 0.05$. Analysis of simple correlation coefficient among the different soil physical and biochemical properties was also carried out to reveal the magnitude and direction of relationships.

[3] The third-level of the administrative divisions of Ethiopia – after zones and region respectively

2.3 Result and Discussion

2.1.3 Physical soil properties: textural class, bulk density, and total porosity

Textural class: Clay fractions dominated the soil in the study area, and the textural class was clayey in all soils across the different AESs of the Choke except in AES 3 of the soil, which was clay loam. There is no significant difference in soil clay and sand content among the AES of the Choke Mountain watershed. Nevertheless, the soil's sand fraction among physical properties varied with a CV of 40% among the AES, with moderate variability according to the classification set by Phil-Eze (2010). The clay content of the soils was higher in the midland plain (AES 3) of the watershed, and such soils can resist soil erosion and are less susceptible to erosion hazards. Thus, it is possible to infer from the results that most soils in the midland areas can be considered less erodible. The result agreed with Teshome et al. (2020), reporting that soils in the upland regions, characterized by clay and silt, were less vulnerable to soil erosion.

The results of ANOVA reveal that the silt content of the soil was statically significant ($P < 0.05$) among AESs of the watershed. The highest mean value of the silt fraction of the soil was observed in AES 5 of the Choke. The overall average percentage distribution of the sand fraction varied from 18.22% in soils of AES 3 to 26.67% in soils of AES 5, a hilly and mountainous highland in the Choke watershed (Table 2.1). This might be attributed to AES 5 being more susceptible to erosion, and most of the fine particles were washed away and deposited in the lowland part of the watershed. Thus, applicable and sustainable soil erosion control measures should be taken to reverse soil degradation in the mountainous highlands of the watershed.

Bulk density: although the higher (1.11g cm^{-3}) and the lower (0.98 g cm^{-3}) bulk density (BD) were observed in AES 2 and AES 4 of the watershed, respectively, no significant difference was found among the AES. Whereas AES 4 of the watershed is an area where cultivation is difficult because of its sloppiness and is affected by erosion and shallow depth, BD is lower than other AESs. Soils with higher organic matter content tend to have lower bulk density. Intensive cultivation and overgrazing might have caused higher BD in AES 2 of the watershed. In agreement, Elias et al. (2022) and Lemenih et al. (2005) also showed high BD in areas where intensive cultivation and free grazing are common.

Table 2.1 Textural and physical properties of soil in the Choke agroecosystems

Agroecosystems of Choke	Clay	Silt	Sand	Textural class	BD	Total Porosity (%)
		(%)			(g cm^{-3})	
AES 1	58.20[a]	25.40[a]	16.40[b]	Clay	1.02	61.75[a]
AES 2	53.67[a]	25.00[a]	21.33[a]	Clay	1.11	58.17[a]
AES 3	60.78[ab]	21.00[ab]	18.22[c]	Clay Loam	1.01	62.00[a]
AES 4	52.75[a]	26.67[a]	20.58[a]	Clay	0.98	63.71[b]
AES 5	43.00[ac]	30.33[ac]	26.67[d]	Clay	1.00	62.25[a]
F	2.172	2.925	1.68		NS	1.271
Sig.	0.089	0.031	0.173		0.335	0.301
CV	29.09	31.60	40.17		12.61	7.81
SE	2.23	1.20	1.25		0.02	0.78

Note: AES 1, lowland and valley fragmented; AES 2, midland plain dominated by vertisol; AES 3, midland plain dominated by Nitosols; AES 4, sloppy midland land; AES 5, hilly and mountainous highlands; BD, bulk density; NS, not significant; CV%, coefficient of variation; SE, standard error; and values followed by the same letter within columns are not significantly different at $p < 0.05$ between AES

2.1.4 Bio-chemical properties: exchangeable base, CEC, soil reaction, total nitrogen, available phosphorus, and organic matter

Exchangeable Base: The exchangeable bases (Ca, Mg, and Na) in the soil can differ depending on the soil's CEC. Ca significantly ($P < 0.05$) varied across AESs of the Choke watershed. The overall mean value of Ca ranged from 1.78 cmol kg^{-1} in AES 3 to 32.98 cmol kg^{-1} in AES 2 of the watershed (Table 2.2). The result shows a very high variability of Ca with 104.0% of the CV (Table 2.3). This might be attributed to variations in landscape, farming practice, and climate variability among AESs of the Choke watershed. Agroecosystems had a significant ($P < 0.05$) effect on Mg. Like Ca, Mg was also high in AES 2 of the Choke, while the lowest mean value of Mg was observed in AES 3. The average exchangeable sodium (Ex. Na) across the overall AESs of the watershed ranged from 0.3 to 0.14 cmol kg^{-1} (Table 2.2). As the result of ANOVA revealed, Na was significantly ($p < 0.01$) different among the agroecosystems. The variation of such an exchangeable base might be attributed to soil erosion and leaching of the bases from sloppy and mountainous highlands.

A study by Negassa and Gebrekidan (2001) revealed that variations in the distribution of exchangeable bases depend on the particle size distribution, degree of weathering, soil management practices, climatic conditions, and intensity of cultivation. Similarly, Fetene and Amera (2018) also show that leaching, limited recycling of crop residues in the soil, continuous cropping, and soil erosion might have contributed to the depletion of basic cations of the soil.

Cation exchange capacity. The AES of the watershed had a significant *(P* < 0.01) effect on the CEC values of the soils in the research area (Table 2.2). Choke's AES 2 had the highest mean CEC value compared to the other AES. According to Landon's (1991) rating, the CEC of the surface soil of the study area was rated medium to high. Although such soil is valuable for agriculture, low SOM concentration and soil compaction (waterlogging) are the major problems.

Table 2.2 Exchangeable base and CEC of the soil in agroecosystems (AES) of the Choke watershed in Ethiopia

Agroecosystems of Choke	Ca	Mg	Ex. Na	Ex. K	CEC (meq/100g)
			cmol kg^{-1}		
AES 1	31.75^{a}	7.84^{a}	0.07^{a}	0.61^{a}	41^{a}
AES 2	32.98^{a}	13.63^{b}	0.14^{b}	0.87^{a}	50.75^{b}
AES 3	1.78^{b}	3.04^{c}	0.03^{a}	1.06^{b}	27.12^{c}
AES 4	9.62^{b}	4.76^{c}	0.03^{a}	0.96^{a}	38.89^{a}
AES 5	12.97^{c}	5.23^{ac}	0.05^{a}	0.45^{c}	39.3^{a}
F	13.545	15.082	7.059	1.306	12.012
Sig	0	0	0	0.282	0
CV	104.04	69.19	100.9	83.47	25.37
SE	2.4	0.66	0.01	0.1	1.45

Note: AES 1, lowland and valley fragmented; AES 2, midland plain dominated by vertisol; AES 3, midland plain dominated by Nitosols; AES 4, sloppy midland land; AES 5, hilly and mountainous highlands; Ca, exchangeable calcium; Mg, exchangeable magnesium; Ex. Na; exchangeable sodium; Ex. K, exchangeable potassium; CEC, cation exchange capacity; CV%, coefficient of variation; SE, standard error; values followed by the same letter along each column are not significantly different at $p < 0.05$ between AES

Furthermore, such a high CEC value provides the soil with a large buffering capacity so that the proper dose of fertilizer can be applied with no immediate adverse effects on the soil (Buraka and Lelago, 2016). CEC is a vital soil quality indicator that shows if the land is productive and capable of retaining and preventing nutrients from being washed away (Aprisal et al., 2019). On the other hand, the medium CEC values on the surface show the potential danger of nutrient losses because of leaching, nutrient mining through harvesting and erosion observed in AES 3 of the watershed.

***pH (H_2O)*:** The results of the study show a substantial variation of soil pH (H_2O) among AESs of the Choke Mountain watershed ($P < 0.05$) (Table 2.3). The overall mean pH value varies from 5.3 to 6.97 across the watershed. According to Landon's (1991) ratings, the reaction of soil in the Choke Mountain watershed ranges from strongly acidic (soils in AES 3) to neutral (AES 1) with a low CV. The relatively lower degree of variation in pH observed by this study is consistent with Bewket and Stroosnijder (2003) and Ebabu et al. (2020), who reported low variation in the pH of soils from different land use types. In agreement with the current study , Al Alwani and Al-Shaye (2019) also found that climate variability and management practices could cause the variability of soil reactions from one place to another. Addition of lime, therefore, could be needed to reach optimum pH for those agroecosystems affected by acidity (AES 3 & 4).

Total nitrogen: Results of ANOVA revealed that TN was significant ($P < .05$) among AES of the watershed with a 58% CV. The average TN values ranged from 0.15% in AES 1 to 0.35% in AES 5 among the watershed, showing a positive and strong correlation with OM (Table 2.4). According to Landon's (1991) rating, TN ranged from low to medium. The concentration of TN was medium in all AES of the Choke watershed except AES 1, and becomes a detrimental impact on the soil's fertility, resulting in a lower capacity for buffering and fewer microorganisms.

***Available Phosphorous*:** AES had a significant ($p < 0.05$) effect on available P, with the highest mean value in AES 4 and the lowest in AES 3 of the Choke Mountain watershed with a very high (169%) coefficient of variation (Table 2.3). Based on Phil-Eze's (2010) classification of CV, available P is one among the soil quality indicators that was the most variable among the five AES of the Choke. In agreement, Ebabu et al. (2020) also found available P was a highly variable attribute of soil quality within the three agroecological zones, showing the variation in the addition or application of di-ammonium phosphate, a concentrated fertilizer with high phosphorus content, to soils of AES of the watershed. According to FAO (1980) ratings, soils with > 25, 18-25, 10-17, 5-9, and < 5mg kg^{-1} are classified as very high, high, medium, low, and very low, respectively. Grounded on this range, AES 4 and 1 of the Choke watershed have a medium available P, whereas AES 5 has a low available P, and AES 2 and AES 3 have a very low, which is deficient available P. The alkaline soils in the lowland valley of the Abay basin may be responsible for the higher soil available P in the study area. On the other hand, in acidic soils, Fe and Al oxides and hydroxides can react with phosphorus to form highly insoluble compounds. For example, iron phosphate (FePO4) and aluminum phosphate (AlPO4) are forms of phosphorus that are not easily accessible to plants. These compounds are stable and tend to remain in the solid phase, reducing phosphorus availability.

Table 2.3 Soil reaction, organic matter, total nitrogen, and available phosphorus in the soils of agroecosystems of Choke watershed in Ethiopia

Agroecosystems of Choke	pH (H_2O)	OM (%)	TN (%)	Ava. P (mg kg^{-1})
AES 1	6.97[a]	2.59[a]	0.15[a]	11.95[a]
AES 2	6.59[a]	3.72[a]	0.22[a]	4.83[a]
AES 3	5.30[b]	3.82[a]	0.23[a]	3.96[a]
AES 4	5.53[b]	5.01[ab]	0.29[a]	16.03[a]
AES 5	5.59[b]	6.32[b]	0.35[b]	5.61[a]
F	28.556	4.327	3.178	2.993
Sig	0	0.005	0.023	0.029
CV	14.09	62.74	58.33	169.55
SE	0.12	0.42	0.02	2.10

Note: AES 1, lowland and valley fragmented; AES 2, midland plain dominated by vertisol; AES 3, midland plain dominated by Nitosols; AES 4, sloppy midland land; AES 5, hilly and mountainous highlands; OM, organic matter; TN, total nitrogen; Ava. P, available phosphorus; CV%, coefficient of variation; SE, standard error; values followed by the same letter within columns are not significantly different at $p < 0.05$ between AES

Jensen (2010) supported the result and reported soils with inherent pH values between 6.5 and 7.5 are ideal for P availability, as in AES 1 of the watershed. When calcium is the dominant cation at high pH, phosphate precipitates with calcium (Prasad & Chakraborty, 2019). On the contrary, AES 4 of the Choke watershed is strongly acidic with a low pH value but with a medium available P.

Organic matter: The variation and distribution of OM among the five AES of Choke were high (62%), as shown in Table 2.5. The results revealed that the overall average value of OM across the watershed was highest in AES 5 and lowest in AES 1. In the lowland and valley fragmented part of the Abay basin, the content of OM was low (2.59%) according to the critical levels adopted by Tadesse et al. (1991). The difference in soil OM across the five AES of the watershed could be responsible for the local climate, farming system, and land use land cover, and dominant soil type of the specific area (Mesfin et al., 2022). In line with this study, Abate and Kibret (2016) additionally demonstrate that the most likely causes of variations in SOM composition amongst the geographical units could be variations in altitude, the intensity of tillage, farming system, and soil management practices. In the mountainous part of the watershed (AES 5), the temperature is low (7.5°C–10°C), which can slow down the decomposition of SOM, while in the lowland part (AES 1), high temperature handles the rapid degradation of OM, thus resulting in the low content of SOM in those areas. The result was confirmed by Bewket and Stroosnijder (2003).

2.4 Correlation Analysis of Soil Quality Parameters

The clay content of the soil fraction significantly and negatively correlated with silt ($r = -0.9$, $P < 0.01$) and sand ($r = -0.9$, $P < 0.05$) contents (Table 2.4). This shows that soils in various agroecosystems with variations in climate, topography, and farming practice result in the concentration of sand content because of the selective removal of the clay and silt fractions, consequently decreasing water and nutrient holding capacity and increasing susceptibility to soil erosion through time.

CEC significantly and positively correlated with the content of OM ($r = 0.3$, $p < 0.05$) and silt content of the soil ($r = 0.2$, $P = 0.05$). Therefore, it is likely that most of the plant's available soil nutrients are derived from OM. The correlation of CEC with OM ($r = 0.3$) is stronger than that of

CEC with the silt content ($r = 0.2$), implying that OM plays a more significant role in supplying plant-available soil nutrients than the silt fraction of the soil in the study area. CEC was also significantly and positively influenced by soil pH ($r = 0.5$, $P < 0.01$), PBS ($r = 0.6$, $P < 0.01$), Ca ($r = 0.7$, $P < 0.01$), Mg ($r = 0.7$, $P < 0.01$), and Ex. Na ($r = 0.6$, $P < 0.01$) contents (Table 2.4). Therefore, OM, silt fractions, pH value, and exchangeable bases are the major soil quality parameters determining CEC and, thus, the adsorbing and exchanging capacity of plant-available soil nutrients in the Choke watershed agroecosystems. Similar results were observed by Guteta and Abegaz (2017) in the Arsamma watershed, Southwestern highlands of Ethiopia.

Table 2.4 Correlations between soil properties in agroecosystems of Choke Mountain watershed in Ethiopia

	Clay	Silt	Sand	BD	Porosity	Ca	Mg	Ex. Na	Ex. K	CEC	PBS	pHH2O	OM	TN	Av. P
Clay (%)	1														
Silt (%)	-.905**	1													
Sand (%)	-.913**	.651**	1												
BD (g cm^{-3})	.366*	-.331*	-.331*	1											
Porosity (%)	-.371*	.336*	.335*	-.998**	1										
Ca (cmol kg^{-1})	-0.004	-0.005	0.011	0.203	-0.2	1									
Mg (cmol kg^{-1})	0.07	-0.098	-0.031	0.319	-0.319	.814**	1								
Ex. Na (cmol kg^{-1})	-0.01	0.069	-0.049	0.059	-0.066	.373**	.535**	1							
Ex. K (cmol kg^{-1})	0.075	-0.12	-0.019	-0.245	0.258	0.247	0.276	0.008	1						
CEC (meq/100/g)	-.336*	.297*	.314*	-0.018	0.018	.762**	.725**	.485**	0.086	1					
PBS (%)	0.051	-0.041	-0.051	0.206	-0.2	.948**	.835**	.327*	.310*	.615**	1				
pH (H_2O)	0.077	-0.071	-0.069	0.215	-0.206	.891**	.735**	0.277	0.267	.522**	.940**	1			
OM (%)	-.705**	.624**	.656**	-.677**	.679**	-0.108	-0.201	0.158	0.109	.306*	-0.217	-.312*	1		
TN (%)	-.656**	.566**	.625**	-.693**	.693**	-0.121	-0.216	0.166	0.078	0.284	-0.238	-.325*	.977**	1	
Av. P (mg kg^{-1})	0.041	-0.003	-0.071	-0.209	0.223	0.227	0.255	-0.074	.698**	0.136	.318*	.298*	0.073	0.05	1

Note: BD, bulk density; Ca, exchangeable calcium; Mg, exchangeable magnesium; Ex. K, exchangeable potassium; CEC, cation exchange capacity; PBS, percent base saturation; OM, organic matter; TN, total nitrogen; Ava. P, available phosphorus; ** correlation is significant at the 0.01 level (2-tailed); and

* correlation is significant at the 0.05 level (2-tailed).

Soil pH is one of the significant chemical properties that reflects the overall well-being of chemical and biological processes in the soil (Doran & Parkin, 1994). The significantly positive correlation of soil pH with CEC, Ca, Mg, and available phosphorus shows the influence of soil pH on other chemical soil properties (Table 2.4). The positive correlation between pH and Ca is because of higher solubility and more significant potential for hydrolysis of $CaCO_3$ at a higher pH. A similar result was presented by (Somasundaram et al., 2013). However, soil pH negatively correlates with OM and TN (r = 0.3, P = 0.05). This could be explained by the fact that AES affected by low concentrations of OM have a high content of $CaCO_3$ or lime, especially in the lowland valley of the Abay basin (AES 1), where the pH value of the soil is high, and SOM is low. The result contradicts the previous study reporting the positive correlation between OM and pH (Guteta & Abegaz, 2017).

Organic matter is considered a storehouse of many plant nutrients, and it influences multiple other soil properties (Adebo et al., 2020; Cherubin et al., 2017; Glover et al., 2000; Idowu et al., 2008) and plays a crucial role in enhancing soil fertility and agricultural productivity as it recycle the elements back to the soil (Jiang et al., 2020). The positive and significant correlation of OM with total nitrogen and CEC contents of the soils shows the intimate association of OM with other chemical soil properties. Hence, it is likely that more of the soil's nitrogen content is released from the organic fraction than from the inorganic components of the soil.

2.5 Implications of Soil Quality for Agriculture

The soil quality assessment results in each AES of the Choke watershed imply some clue information, primarily from an agricultural perspective. The study found that midland AES (AES 2 & 3), characterized by gentle slopes, have productive soil. As reported by (Mesfin et al., 2022), the overall soil quality index of AES 2 and 3 is better than the soil quality of other AES and create good condition for agriculture. Simane et al. (2013) also found productive and suitable soil types in AES 2 and 3. AES 2 is an intensively cultivated area but is affected by water logging during the rainy season, which is difficult for agricultural activities. On the other hand, AES 3 is affected by soil acidity, an essential constraint for agricultural productivity, followed by available phosphorous and soil nitrogen content (Kshudiram and Mistri, 2015).

Similarly, AES 4 is also affected by acidity, attributed to the sloppiness of the area, and high rainfall causes the leaching of essential nutrients and constrains agricultural production and productivity. In some areas (localities), farmers have even abandoned their lands because of low crop productivity. The cropping pattern in the area has also changed from initially grown crops (wheat and barley) to low-value crops (Engido-*Avena species*). The local government has initiated the liming program to improve the productivity of acid soils. Despite the effort, almost all farmers are not using liming to reclaim their lands (Simane et al., 2013).

AES 1 and AES 5 are not suited for agricultural production, as are low fertility soils, steep slopes, and shallow soils, according to the results of physical and biochemical soil parameter assessment. Additionally, AES 1 is an adverse agroecological environment with less consistent rainfall than other AES.

2.6 Conclusion

This study found that farming systems with various soil management practices, land use land cover, agroclimatic variability of the area, and soil type of AES with varying landscapes were the essential elements causing the variation of physical-biochemical soil characteristics in the Ethiopian highlands in general and particularly in the agroecosystems of Choke Mountain watershed. The result revealed that the measured soil quality attributes varied significantly across the study watershed. Clay fractions dominated the soil in the study area, and the textural class was clayey in all soils across the five AES except in AES 3 of the soil, which was clay loam. The highest mean silt and sand content was observed in AES 5. This might be attributed to increased soil erosion from the upper part of the watershed and deposited in the middle and lower parts of the waters, which contains higher soil clay content. However, the higher SOM and TN were also recorded in AES 5. The lower temperature (7.5°C -10°C) of AES 5 of the watershed, which slows down the decomposition of SOM and less addition of mineral fertilizers to the soil, might be the reason for the higher OM content of the area.

The soil pH of the study area varied from strongly acid soil (AES 3 and 4) to neutral (AES 1) because of the content of $CaCO_3$, rainfall amount, cultivation intensity, and type of soil management. On the other hand, in AES 1-where the temperature was high, SOM content was low. Exchangeable bases (Ca, Mg, and Ex. Na) were the highest in AES, dominated by vertisol soil (AES 2) with high CV%. Nevertheless, the major problem of this type of soil was a low content of OM and waterlogging during the high rainy season. Another essential soil nutrient that varied greatly (CV% = 169%) between AES was available P, observed in deficient amounts except AES 1 and 4. To reverse soil acidity and improve soil fertility status in those AES affected by leaching and nutrient depletion of soil, farmers would be advised to use efficient and practical soil management techniques. In particular, lime and organic fertilizers (compost and manure) are essential. Adopting agroforestry and economically viable multipurpose perennial crops should be promoted to reduce soil erosion for AES with steep slopes in the watershed, improve soil quality and maintain sustainable agriculture and environment in agroecosystems.

CHAPTER THREE

3. VARIABILITY OF SOIL QUALITY INDICATORS ALONG WITH THE DIFFERENT LANDSCAPES OF CHOKE AGROECOSYSTEM, UPPER BLUE NILE BASIN, ETHIOPIA

Abstract

*Understanding the variability of soil quality indicators across topographic positions and agroecosystems (AES) is critical for improving soil fertility, productivity, and environmental sustainability. This study evaluates the variability of soil quality indicators and the different landscape positions (upper, middle, and lower slopes) among the five AES of the Choke Mountain watershed in the upper Blue Nile Basin. A total of forty soil samples were gathered from Choke Mountain's five AES, upper, middle, and lower landscape positions. Principal component analysis (PCA) determined the minimum datasets (MDS) from fourteen soil quality indicators. Using multivariate analysis of variance (MANOVA), the variability of soil quality indices among AES of the Choke and variation with landscape positions was investigated. The interaction effect of AES and topo-sequence (AES*topo-sequence) substantially affects three soil quality indicators, including soil silt content, pH, and available phosphorus. The highest mean value of silt content was found in the upper position of the hilly and mountainous highlands (AES 5), while the lowest was found in the lower part of the midland plain with black soil (AES 2). The highest mean pH of the soil was found in the lower part of the lowland and valley fragments (AES 1), and the lowest was in the lower position of the midland plain with brown soil (AES 3). The highest record of available P was found in AES 1's middle position and the lowest in AES 3's upper positions. AES had a significant impact on cation exchange capacity (CEC), and both AES and topography had a significant and distinct impact on organic matter (OM). Thus, the study suggests site-specific solutions to improve agricultural productivity and ease the constraints associated with each soil in each topo-sequence and AES.*

Keywords: *Agroecosystems, Landscape position, Soil quality indicators, Principal Component Analysis, Multivariate Analysis of Variance, Choke Mountain watershed.*

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3.1 Introduction

Soil is an essential part of humankind's total stock of natural resources and the foundation of food production (Buol et al., 2003). Topography, parent material, climate, biota, and time all play a role in soil formation (Jenny, 1945). Although soil-forming processes handle all spatial patterns, our knowledge of the determinants, particularly topographic influence, is inadequate (Amhakhian & Achimugu, 2011). Most surface processes on the planet, such as soil formation and development, are influenced by topography (Lawal et al., 2013). Soil parameters vary in vertical and horizontal directions due to landscape position (slope), soil-forming factors, and land use (Adegbite et al., 2019; Baskan et al., 2016). Topography influences soil's physical and chemical qualities and the pattern of soil distribution throughout the landscape (Dessalegn et al., 2014; Fawole et al., 2016). The soil differs at different topographic positions because of the undulating landscape (Adegbite et al., 2019; Amhakhian & Achimugu, 2011; Atofarati et al., 2012). These affect soil-water connections, rainfall, drainage, soil erosion, textural composition, and other soil qualities, significantly impacting field plant growth (Atofarati et al., 2012).

It has been shown that understanding the relationship between landscape and soil properties enhances the effort to improve soil fertility, quality, and productivity. In mountainous areas like Choke, soil properties vary from the summit to the toe slope along a topo-sequence. Microclimate, pedogenesis, and geologic processes contributed to variations in soil properties (Nuga et al., 2008; Ziadat et al., 2010). Topography-based soil quality studies are also commonly acknowledged to have a vital influence on the process that controls how soils are distributed and used in the landscape (Esu et al., 2008).

Various researchers have investigated soil-landscape position relationships elsewhere. Dessalegn et al. (2014) reported that soil organic carbon (SOC), total nitrogen (TN), available phosphorous (Ava. P), and cation exchange capacity (CEC) have increased from the upper to the lower slope positions. Miheretu & Yimer (2018) found increasing clay content, pH, organic matter, total nitrogen, available phosphorous, and percent base saturation (PBS) downslope due to soil erosion from the upper slopes to the lower slopes. Bufebo et al. (2021) found that landscape position considerably affected soil quality indicators. Lower landscape positions have the highest mean value of soil organic carbon, total nitrogen, carbon to nitrogen (C/N) ratio, available P, CEC, exchangeable bases, and micronutrients. Mulugeta and Sheleme (2010) also found that soil quality indicators were altered with varied landscape positions.

Agroecosystems (AES), a combination of agroecology, soil, terrain, and farming system distribution, significantly affect soil quality indicators (Simane et al., 2013). In a geographic location where various physiographic features like steep slopes, hilly lands, and mountainous surfaces are prevalent, topographic features, climatic elements, and vegetation cover significantly influence and characterize soil properties (Mohammed et al., 2018). Because of high biomass production and increased soil respiration, AES accumulates high SOC stocks in cooler and moister climates, whereas warm and moist AES accumulate moderate SOC stocks (Abebe et al., 2020). According to Bewket & Stroosnijder (2003), in Ethiopia's Choke Mountain watershed and Yimer et al. (2006), in Ethiopia's Bale Mountain, higher altitudes have higher carbon content than lower altitudes. Teferi et al. (2016) found higher OM content in the midland and lower OM in the upland of the Jedeb watershed. Such disparities in findings across different elevations and positions and earlier studies' limited geographical coverage showed the need for more site-specific research to accommodate the country's vast biophysical and socio-economic diversity and the Choke watershed, particularly across the entire AES. This study thus identifies, selects, and compares soil quality indicators of the different topo-sequences across the five AES of the Choke watershed.

The objectives of this study were to (i) identify key soil quality indicators and (ii) investigate the variability of selected soil quality indicators in different landscape positions (upper-middle-lower) across and within the five AES of Choke watersheds in the upper Blue Nile Basin, Ethiopia.

3.2 Materials and Methods

3.2.1 Soil sample collection procedures

The writers carried out a general visual field survey, or transect walk, to view the variations across the five AES of the Choke watershed. Then, five Woredas[4] (one from each AES) were selected randomly, and fifteen Kebeles[5] (three from each Woreda) were selected based on their topo-unites from the Digital Elevation Model (DEM) with a 30m resolution. Three topo-unites, summit (upper part), back slope, and toe slope (lower slope) were selected from each AES.

A total of forty (5, 9, 9, 8, and 9 from AES 1, AES 2, AES 3, AES 4, and AES 5, respectively) composite soil samples were gathered using a hand auger from three slop positions in each of the five AESs of Choke watershed. The composite soil samples from five sub-samples were thoroughly mixed in a clean bucket to take 1 kg of soil from four corners and the center of a square plot of 10m by 10m at a depth of 20 cm. This study's top 20 cm of soil depth is considered, as the depth contains the highest concentrations of many soil properties and has the most decisive response to slope difference (Miheretu & Yimer, 2018). Thirty-three undisturbed core soil samples were sampled from the representative locations using a sharp-edged steel cylinder (6 cm long with a 6 cm diameter) from the surface soil for BD analysis using the core method. To minimize outlying results, unwanted materials, such as dead plants, sediment deposits, furrows in the field, and organic piles, were excluded from the specific sampling sites.

3.2.2 Soil lab analysis

The soil samples were placed correctly in plastic bags and taken to the national soil testing center for laboratory analysis. The samples were air-dried, crushed, and ground using a pestle and mortar and passed through a 2 mm sieve, except for SOC and TN. A 0.5 mm sieve mesh was needed to prepare organic carbon and nitrogen (Sahlemedhin and Taye, 2000).

[4] The third-level of the administrative division of Ethiopia – after zones and the regional states.
[5] The smallest administrative unit in Ethiopia

The sample soil was analyzed following the standard soil analytical procedures. Soil particle size distribution was determined by the Bouyoucos hydrometric method (Bouyoucos, 1962). Undisturbed soil samples were collected using a core sampler to measure bulk density (Sahlemedhin and Taye, 2000) at the soil laboratory center of Addis Ababa University, Ethiopia.

BD= oven-dry weight of soil/volume of soil

The total porosity of the soil was determined as follows:

$$P = (1 – BD)/d) \times 100$$

Where P is total porosity (%), BD is the bulk density (g/cm^3), and d is the particle density equal to 2.65 g/cm^3 (Landon, 1991).

Soil pH was measured in a 1:2.5 soil to water suspension following the procedure outlined by Sahlemedhin and Taye (2000). The total nitrogen content was determined using the Kjeldahl method (Jackson, 1958) by oxidizing soil samples with sulfuric acid and converting the N compounds into $NH4^+$ as ammonium sulfate. The Walkley & Black (1934) wet digestion method was used to determine soil carbon content, and the percent SOM was calculated by multiplying the percent soil organic carbon by a factor of 1.724. Phosphorus was measured according to the standard procedure of the Olsen et al. (1954) extraction method and measured by a spectrophotometer. The ammonium acetate technique determined the CEC and exchangeable bases (Black, 1965). Calculations of the exchangeable Ca and Mg from the extract were made using an atomic absorption spectrophotometer. The exchangeable K and Na were determined using a flame photometer from similar entities. Divide the sum of base cations by the cation exchange capacity multiplied by 100 to get the proportion of percent base saturation (Landon, 1991).

3.2.3 Statistical analysis

Descriptive statistics on soil quality properties were analyzed. Their normality distribution was tested with the Shapiro-Wilk test of the standardized variable to proceed with further analysis. A logarithmic transformation is applied to normalize non-distributed data.

Kaiser-Meyer-Olkin (KMO) was employed to test the sampling adequacy (Kaiser, 1974). The sample is adequate if the value of the KMO test is above the acceptable level of 0.5 (Kaiser, 1974; Kaiser, 1970). The strength of the association between variables is measured using Bartlett's test of sphericity. Small values of the significance level ($P < 0.05$) show that factor analysis may be helpful in data (Bartlett, 1954).

Principal component analysis (PCA) was performed on the soil quality parameters-dependent variables, meeting the preliminary assumption of examining the relationship among the variables by grouping them into principal components. Then the principal components (PCs) that have an eigenvalue of over one (1) are kept and selected for further analysis (Andrew & Carroll, 2001; Kaiser, 1960; Rezaei et al., 2006). Factor scores for each sample were computed using the regression method to analyze variance. The correlation was conducted for factor scores to select the type of rotation. Under each PC, weighted variables (> 0.7) (Teferi et al., 2016; Tesfahunegn & Gebru, 2020a) were selected as soil quality indicators. Multivariate correlation coefficients were employed to check for redundancy and correlation between these highly weighted variables (Andrews et al., 2002; Vasu et al., 2016). If the variables are well-correlated ($r > 0.60$), the variables with the largest factor loading (absolute value) are preserved as an indicator (Mukherjee & Lal, 2014; Sánchez-Navarro et al., 2015; Tesfahunegn & Gebru, 2020a).

Analysis of variance (ANOVA) was employed on the selected soil quality indicators to determine their significant variation in AES and topo-sequence. The significant components were then subjected to a factorial MANOVA ($p < 0.05$). A multiple comparison test (LSD) was applied to compare the effects of the AES, topo-sequence, and their interaction on selected soil quality parameters. All the tasks were performed using the General Linear Model (GLM) procedures in SPSS (Ver.26). The magnitude of the effect of AES, topo-sequence, and their interaction was checked by looking at partial eta squared (Cohen, 1988). According to the accepted criteria of Cohen (1988), partial eta squared values ranged from 0 to 1, where 0-0.2 is a minor effect, 0.2-0.5 is medium, and over 0.5 is a large scale.

3.3 Results

3.3.1 Statistical analysis of measured soil quality indicators

The descriptive analysis revealed a numerical difference among the selected soil quality indicators in the agroecosystems of the Choke Mountain watershed across the different topographic positions. The analysis also showed significant statistical variation among the selected and measured soil quality parameters because of variations in AES and slope positions (Table 3.1).

Table 3.1 Soil quality properties (n = 40) to agroecosystems and slope positions in the Choke watershed (mean ± standard error)

SQI	AES 1	AES 2	AES 3	AES 4	AES 5	Total	Upper	Middle	Lower	Total
Clay (%)	58.2±2.94 ^{a}	53.67 ± 5.29^{a}	60.78 ± 2.46^{ab}	53.5 ± 5.8 ^{a}	42.67 ± 6.91^{ac}	53.32 ± 2.48	42.79 ± 4.38^{a}	62.62 ± 1.67^{b}	55.38 ± 4.33^{ab}	53.32 ± 2.48
Silt (%)	25.4±2.04 ^{a}	25 ± 2.79 ^{a}	21 ± 1.2^{ab}	26.75 ± 3.69^{a}	31 ± 3.54^{ac}	25.85 ± 1.36	32.57 ± 2.48^{a}	21.92 ± 1.1^{b}	22.54 ± 1.95^{b}	25.85 ± 1.36
BD (g cm^{-3})	1.02 ± 0.03	1.11 ± 0.08	1.00 ± 0.02	0.98 ± 0.04	0.99 ± 0.05	1.02 ± 0.02	0.98 ± 0.04	1.08 ± 0.05	1.01 ± 0.02	1.02 ± 0.02
Porosity (%)	61.75 ± 0.95 ^{a}	58.17 ± 2.89 ^{a}	62 ± 0.82^{b}	62.8 ± 1.62^{b}	62.67 ± 1.91^{b}	61.58 ± 0.82	63.08 ± 1.38^{a}	59.5 ± 1.88^{a}	61.82 ± 0.83^{a}	61.58 ± 0.82
pH (H_2O)	6.97 ± 0.64 ^{a}	6.59 ± 0.18 ^{a}	5.3 ± 0.06^{b}	5.23 ± 0.13^{b}	5.59 ± 0.09^{b}	5.85 ± 0.14	5.56 ± 0.17^{a}	5.82 ± 0.21^{ab}	6.20 ± 0.31^{bc}	5.85 ± 0.14
CEC (meq/100g)	41.00 ± 5.24 ^{a}	50.75 ± 0.82 ^{b}	27.12 ± 1.06^{c}	36.27 ± 1.37^{a}	39.78 ± 3.26^{a}	38.85 ± 1.67	39.52 ± 2.56^{b}	37.13 ± 2.87^{b}	39.84 ± 3.4^{b}	38.85 ± 1.67
Mg (cmol kg^{-1})	7.84 ± 0.26 ^{a}	13.63 ± 0.78 ^{b}	3.04 ± 0.33^{c}	2.2 ± 0.81^{c}	4.67 ± 0.47^{ac}	6.22 ± 0.75	5.7 ± 1.37^{a}	6.15 ± 1.17^{a}	6.86 ± 1.44^{a}	6.22 ± 0.75
Ca (cmol kg^{-1})	31.75±10.97 ^{a}	32.98 ± 5.12 ^{a}	1.78 ± 0.50^{b}	3.04 ± 1.38^{b}	13.20 ± 2.87^{c}	15.3 7 ± 2.78	1.00 ± 2.66^{a}	13.45 ± 4.82^{ab}	23.06 ± 6.17^{bc}	15.37 ± 2.78
Ex. Na (cmol kg^{-1})	0.07 ± 0.02 ^{a}	0.13 ± 0.03 ^{b}	0.03 ± 0.01^{a}	0.02 ± 0.0^{a}	0.05 ± 0.01^{a}	0.06 ± 0.01	0.07 ± 0.02^{a}	0.07 ± 0.02^{a}	0.05 ± 0.01^{a}	0.06 ± 0.01
Ex. K (cmol kg^{-1})	0.61 ± 0.17 ^{a}	0.87 ± 0.2 ^{a}	1.06 ± 0.22^{b}	0.51 ± 0.1^{a}	0.42 ± 0.08^{c}	0.71 ± 0.08	0.59 ± 0.12^{b}	0.73 ± 0.17^{b}	0.81 ± 0.14^{b}	0.70 ± 0.08
PBS (%)	94.51±23.29 ^{a}	92.47 ± 9.45 ^{a}	21.77 ± 2.60^{b}	16.56 ± 6.2^{b}	44.95 ± 5.37^{b}	50.94 ± 6.43	37.51 ± 7.86^{a}	47.12± 9.57^{ab}	69.22 ± 14.29^{bc}	50.94 ± 6.43
OM (%)	2.59 ± 0.48 ^{a}	3.72 ± 0.88 ^{a}	3.82 ± 0.20^{a}	4.74 ± 0.90^{ab}	6.92 ± 1.57^{b}	4.53 ± 0.48	5.94 ± 0.88^{a}	3.17 ± 0.27^{ab}	4.35 ± 1.02^{bc}	4.52 ± 0.48
TN (%)	0.15 ± 0.03^{a}	0.22 ± 0.89 ^{a}	0.23 ± 0.01^{a}	0.28 ± 0.05^{a}	0.38 ± 0.08^{b}	0.26 ± 0.03	0.33 ± 0.19^{a}	0.19 ± 0.02^{ab}	0.25 ± 0.05^{bc}	0.26 ± 0.03
Av. P (mg kg^{-1})	11.95 ± 2.67^{a}	4.8 ± 0.90 ^{a}	3.96 ± 0.78^{a}	4.69 ± 0.94^{a}	5.42 ± 0.67^{a}	5.62 ± 0.61	5.7 ± 0.7^{ab}	4.73 ± 1.22^{a}	6.43± 1.22^{b}	5.62 ± 0.6

Note: SQI, soil quality indicators; BD, bulk density; CEC, cation exchange capacity; Ca, calcium; Mg, magnesium; Ex. Na; exchangeable sodium; Ex. K, exchangeable potassium; PBS, percent base saturation; OM, organic matter; TN, total nitrogen; Ava. P, available phosphorus; values followed by the same letter along each row are not significantly different at $p < 0.05$ among agroecosystems and slope positions

3.3.2 Grouping and selecting a minimum data set

The Kaiser-Meyer-Olkin (KMO) measure tested the sampling adequacy for factor analysis, KMO = 0.62, showing that it is above the acceptable level of 0.5. Bartlett's test of sphericity had an associated *P* value of less than 0.001, which was highly significant (x^2 (91) = 655.91, *P* = 0.000), which justified continuing and performing accurate factor analysis. Four components with eigenvalues above Kaiser's criterion of 1 were kept.

In combination, principal components (PCs) explained 84.35% of the variability in the measured dependent variables including clay, silt, BD, porosity, pH, CEC, Ca, Mg, Ex. K, Ex. Na, OM, Nitrogen, and available P (Table 3.2). The first principal component (PC 1) accounts for nearly 39% of the total variance with high loadings (> 0.7). Component 1 was correlated with variables, including clay and silt content, BD, porosity, OM, and TN. The second PC explained 26.5% of the variance with high loadings and positively correlated pH, CEC, Ca, Mg, and PBS variables. Component 3 accounted for 10% of the total variance with high loadings from available P with a positive correlation. Component 4 explained 8.77% of the total variance with high loading from exchangeable K (Table 3.2).

The indicator's communality score determines the proportional importance of the soil quality characteristic. Communalities calculated the proportion of each soil indicator's variance explained by the four components. Principal components (PCs) accounted for over 93% of the variation in soil pH, Ca, PBS, and OM; > 90% in BD, porosity, Mg, and total nitrogen; > 84% in CEC, silt, and clay content; > 62% in exchangeable Na and available P, and the last and most negligible contribution was explained by > 52% in exchangeable K (Table 3.2).

Table 3.2 The factor loadings after Varimax rotation and communality estimates (factor loadings > 0.7 appear bold, and the underlined variables were kept as MDS) (n = 40)

	PC				
Soil Quality Indicators	PC 1	PC 2	PC 3	PC 4[6]	Communality Estimates
Clay (%)	**-0.829**	0.006	-0.347	0.258	0.875
Silt (%)	**<u>0.773</u>**	-0.016	0.365	-0.344	0.849
BD (g cm^{-3})	**-0.766**	0.136	0.074	-0.541	0.904
Porosity (%)	**0.768**	-0.133	-0.057	0.547	0.91
pH (H_2O)	-0.294	**<u>0.786</u>**	0.467	0.092	0.931
CEC (meq/100g)	0.348	**<u>0.822</u>**	-0.041	-0.246	0.859
Ca (Cmol kg^{-1})	-0.107	**0.937**	0.247	-0.024	0.951
Mg (Cmol kg^{-1})	-0.297	**0.899**	-0.079	-0.136	0.922
Ex. Na (Cmol kg^{-1})	0.086	0.637	-0.446	-0.11	0.625
Ex. K (Cmol kg^{-1})	-0.08	-0.093	0.112	**0.708**	0.529
PBS (%)	-0.242	**0.871**	0.358	0.033	0.946
OM (%)	**<u>0.951</u>**	-0.122	-0.106	-0.024	0.931
TN (%)	**0.937**	-0.102	-0.164	0.02	0.916
Ava. P (mg kg^{-1})	0.097	0.222	**<u>0.773</u>**	0.085	0.663
Initial eigenvalues	5.458	3.712	1.411	1.228	
Variance (%)	38.988	26.518	10.076	8.772	
Cumulative (%)	38.988	65.506	75.582	84.354	

Note: PC, principal components; BD, bulk density; CEC, cation exchange capacity; Ca, calcium; Mg, magnesium; Ex. Na; exchangeable sodium; Ex. K, exchangeable potassium; PBS, percent base saturation; OM, organic matter; TN, total nitrogen; Ava. P, available phosphorus.

Correlation coefficients show that there were variables in PC 1 that were well-correlated (r > 0.60) (Table 3.3). Thus, variables with the highest absolute value factor loading (silt and OM) were kept as the minimum dataset from PC 1, naming PC 1 as "root penetration and water retention."

[6] The effects of AES, topo-sequence, and interaction of the two (AES x topo-sequence) on PC 4 are not significant ($P < 0.05$). Therefore, PC 4 (exchangeable K) was not analyzed in MANOVA and the discussion part.

Table 3.3 Pearson correlation coefficients of soil quality indicators (n = 40)

SQIs	BD	Porosity	Silt	Clay	pH (H_2O)	CEC	Ca	Mg	Ex. Na	Ex. K	PBS	OM	TN
BD (g cm^{-3})	1												
Porosity (%)	-.998**	1											
Silt (%)	-.381*	.386*	1										
Clay (%)	.416*	-.422*	-.902**	1									
pH (H_2O)	0.295	-0.284	-0.06	0.056	1								
CEC (meq/100g)	0.02	-0.017	0.294	-.333*	.532**	1							
Ca (cmol $kg^{-1)}$	0.262	-0.257	-0.011	-0.001	.897**	.760**	1						
Mg (cmol kg^{-1})	.423*	-.424*	-0.105	0.078	.740**	.728**	.815**	1					
Ex. Na (cmol kg^{-1})	0.03	-0.034	0.078	-0.02	0.303	.519**	.400*	.604**	1				
Ex. K (cmol kg^{-1})	-0.138	0.148	-0.125	0.029	0.202	0.035	0.219	0.171	0.141	1			
PBS (%)	0.287	-0.281	-0.041	0.049	.948**	.615**	.953**	.825**	.377*	0.223	1		
OM (%)	-.688**	.690**	.627**	-.715**	-.340*	0.282	-0.136	-0.241	0.177	0.074	-0.252	1	
TN (%)	-.709**	.709**	.568**	-.667**	-.348*	0.266	-0.143	-0.247	0.177	0.053	-0.266	.977**	1
Ava. P (mg kg^{-1})	-0.073	0.091	0.208	-0.164	.537**	0.263	.439**	0.151	0.214	0.123	.440**	0.022	0.009

Note: SQIs, soil quality indicators; BD, bulk density; CEC, cation exchange capacity; Ca, calcium; Mg, magnesium; Ex. Na; exchangeable sodium; Ex. K, exchangeable potassium; PBS, percent base saturation; OM, organic matter; TN, total nitrogen; Ava. P, available phosphorus; ** Significant at the 0.01 level (2-tailed). * Significant at the 0.05 level (2-tailed)

The correlation coefficients of variables included under the principal component-2 revealed that percent base saturation (PBS) was well-correlated with pH, Mg and Ca, and Mg was well-correlated with pH, CEC, and Ca (Table 3.3). Hence, only pH and CEC were kept as a MDS from PC 2 and named "nutrient retention and availability". Available P was the only high-loading variable in principal component-3 (Table 3.4) and was kept as MDS of soil quality indicators from PC 3 and named as "Macro-nutrient." Thus, five (silt content, PH, CEC, OM, and available P) of the total soil quality indicators were selected as a MDS.

3.3.3 MANOVA assumption test

The multivariate normality of dependent variables was satisfied, which was checked by a statistically non-significant ($P > 0.05$) result of the Shapiro-Wilk test. Linearity and multicollinearity assumptions were also met. Homogeneity of variance was examined using independent Levene's tests for each dependent variable, and all dependent variables were found to have a statistically non-significant ($P > 0.05$) influence. The non-significant result shows that each dependent variable has the same variance across treatment levels (AES and topo-sequence). Box's test (Box's M = 42.069, $P = 0.019$) of statistically non-significant ($P > 0.001$) (Malo, 2016) results satisfied the assumption of homogeneity of variance-covariance matrices. The dependent variables' covariance matrices were equal across the levels of the treatments. Bartlett's test of sphericity was statistically significant ($\chi 2 = 69.566$, $P = 0.000$), satisfying the strength of the relationship among dependent variables.

3.3.4 Multivariate interaction and main effects on indicator variability

To interpret multivariate tests, the non-significant Box's M test suggests the most robust and commonly used statistics, Wilks' lambda (Table 3.5). The result shows that AES significantly affects the combined dependent variables.

Table 3.4 Result of MANOVA test for the top (0-20cm) soil quality indicators[7]

Effect		Value	F	df	Error df	Sig.	Eta Squared *(η^2)*
AES	Pillai's Trace	2.487	4.656	24	68	.000	0.622
	Wilks' Lambda	0.007	6.415	24	50.05	.000	0.706
	Hotelling's Trace	13.768	7.171	24	50	.000	0.775
	Roy's Largest Root	8.834	25.029	6	17	.000	0.898
Topo-sequence	Pillai's Trace	1.526	8.049	12	30	.000	0.763
	Wilks' Lambda	0.051	8.038	12	28	.000	0.775
	Hotelling's Trace	7.364	7.977	12	26	.000	0.786
	Roy's Largest Root	5.153	12.881	6	15	.000	0.837
AES * Topo-sequence	Pillai's Trace	2.674	2.182	42	114	.001	0.446
	Wilks' Lambda	0.004	3.72	42	69.118	.000	0.603
	Hotelling's Trace	20.741	6.091	42	74	.000	0.776
	Roy's Largest Root	15.445	41.921	7	19	.000	0.939

Note: AES, agroecosystem; η^2, partial eta squared: The effect of topo-sequence, agroecosystem, and interaction effect was significant and extensive when the value of $P < 0.05$ and Eta Squared (η^2) > 0.5.

A separate univariate analysis of variance with the selected soil quality indicators (dependent variables) was conducted as a follow-up test for MANOVA. It was conducted to find a significant group difference for each dependent variable (Table 3.5).

Table 3.5 Univariate test results (n = 40)

Source	Dependent Variable	*F*	Sig.	*Partial Eta Squared*
AES	pH (H_2O)	31.259	.000	0.868
	CEC	9.286	.000	0.662
	Silt	6.775	.001	0.588
	OM	4.687	.008	0.497
	Ava. P	6.153	.002	0.564
Topo-sequence	pH (H_2O)	16.067	.000	0.628
	CEC	0.977	.395	0.093
	Silt	22.979	.000	0.708
	OM	3.442	.048	0.178
	Ava. P	7.961	.003	0.456
AES * Topo-sequence	pH (H_2O)	10.745	.000	0.798
	CEC	1.439	.248	0.346
	Silt	8.509	.000	0.758
	OM	1.869	.132	0.408
	Ava. P.	5.544	.001	0.671

Note: AES, agroecosystem; CEC, cation exchange capacity; OM, organic matter; Ava. P, available phosphorus.

[7] The data from five AES of the Choke watershed along the three topo-sequences was pooled together for this analysis (n = 40)

3.3.5 AES and topo-sequence interaction effect

As depicted in Table 3.5, the interaction effect of AES and topo-sequence (AES*topo-sequence) was statistically significant, and the effects of the magnitude were high on silt content (F = 8.509, P = 0.000, η^2 = 0.758), pH (F = 10.745, P = 0.000, η^2= 0.798) and available P (F = 5.544, P = 0.001, η^2= 0.671).

The highest mean value of silt content was found in the upper position of AES 5, while the lowest was found in the lower part of AES 2. The lowest mean pH of the soil (mean = 4.84) was recorded in the upper position of AES 4, and the highest mean pH of the soil (mean = 8.05) was recorded in the lower part of AES 1. There was also an interaction effect of topo-sequence and AES on available P, with the highest record in AES 1's middle position and the lowest in AES 3's upper slope (Table 3.6).

Table 3.6 Interaction effects of topo-sequence and AES on the three soil quality indicators (mean ± Standard error) (n = 40)

		Agroecosystems of Choke Watershed				
Soil property	Topo-sequence	AES 1	AES 2	AES 3	AES 4	AES 5
Silt (%)	Upper slope	21±2.94	33.66±2.40	22.33±2.40	39±2.40	43±2.40
	Middle slope	25±4.16	24.33±2.40	21±2.40	20.33±2.40	21±2.40
	Lower slope	30±2.94	17±2.40	19.66±2.40	18±2.94	29±2.40
pH (H_2O)	Upper slope	5.41±0.2	6.6 ±0.16	5.36±0.16	4.84±0.16	5.51±0.16
	Middle slope	7.95±0.28	6.09±0.16	5.32±0.16	5.51±0.16	5.66±0.16
	Lower slope	8.05±0.2	7.09±0.16	5.21±0.16	5.39±0.1	5.60±0.16
Ava.P.(mg kg^{-1})	Upper slope	6.00±1.62	7.19±1.32	3.00±1.32	4.86±1.32	7.50±1.32
	Middle slope	18.69±2.29	3.85±1.32	3.70±1.32	3.185±1.32	3.52±1.32
	Lower slope	14.52±1.62	3.34±1.32	5.15±1.32	6.684±1.62	5.24±1.32

Note: AES 1, lowland and valley fragmented; AES 2, midland plain with black soil; AES 3, midland plain with brown soil; AES 4, midland slopping lands; AES 5, hilly and mountainous highlands; Ava. P, available phosphorus.

3.3.6 Main effects of AES and topo-sequence on indicators' variability

The main effect of AES was statistically significant for CEC (F = 9.286, P = 0.000, η^2= 0.868) and OM (F = 4.687, P = 0.008, η^2= 0.497). OM was also significantly affected by the main effects of landscape position (F = 3.442, P = 0.048, η^2= 0.17) (Table 3.5).

3.4 Discussions

This study assessed the variability of soil quality indicators along the various topo-sequences at AES of the Choke Mountain watershed using factorial MANOVA. Silt content, pH, available P, OM, and CEC, are the soil quality indicators related to AES and the landscape position of the watershed. Because the last component had no significant effects, the change in soil attribute of the corresponding component could not be explained by either AES or topo-sequence. A critical review by Bünemann et al. (2018) also recommended that, with the PCA technique, the number of indicators selected typically ranges between 6 and 8. This study's findings are like those of (Teferi et al., 2016). They investigated silt content, bulk density, soil pH, and organic matter as important soil quality indicators for evaluating agroecology or land use.

3.4.1 The soil silt content

The result shows that the silt content of the soil increases with the increasing slope of the watersheds. According to this, a study in Thailand's Wat Chan watershed found a positive, significant connection between topsoil silt and SOM as the slope angle increased (Sangchyoswat & Yost, 2002). These links could be because of the structural aggregation of silt and the accumulation of SOM in the watershed's wet and high-altitude zones.

The silt content of the soil fraction also showed significant variation among the five agroecosystems (AES) and landscape positions ($P < 0.05$). The multivariate effect size statistics revealed the main effects of AES (η^2 = 0.588) and landscape position (η^2= 0.708) were significant (Table 3.6). The AES of Choke significantly affects the silt content of the soil, and the hilly and mountainous highland (AES 5) accounts for the highest value (mean = 31%) of silt (Table 3.1). It could be because of the highest value of the OM in AES 5 with a textural class of clay, while only AES 3 has a clay loam textural class. The result was consistent with Teferi et al. (2016) study on the Jedeb watershed that found altitude significantly affects the silt content, and the upland part (mean = 40.5%) was significantly higher than that of the midland part (mean = 26.9%).

Correspondingly, the soils at the upper landscape position of the watershed had a high mean value of silt (32.8%). In comparison, the lower landscape position had the lowest (21.7%), and the soils in the middle landscape had an intermediate (21.8%) silt content (Table 3.1). In contradiction to this result, Amuyou & Kotingo (2015) and Bufebo et al. (2021) found the highest and lowest mean value of silt content recorded in the lower and upper positions, respectively. Miheretu & Yimer (2018) found that variations in the silt content of the soil were not significant among landscape positions of the Gelana sub-watershed, Northern highlands of Ethiopia.

3.4.2 PH of the soil

The result shows that alkaline soil was found in the lower part of AES 1, according to Landon's (1991) rating. The high calcium carbonate content of the soil within the area of AES 1 of the Choke watershed affected the pH of the soil. In addition, soil erosion affects the pH concentration in AES 1 of the Choke watershed. Since AES 1 is a lowland part of the watershed, the soil was washed away from the upper into the lower part containing nutrients, making the soil alkaline. The lowest mean value (mean = 4.84) with the high acidity of soil pH was reported in the upper position of sloppy midland land (AES 4) (Table 3.6). It might be attributed to leaching off base ions (Ca, Mg, and K) because of high erosion in AES 4. There is a high mean annual rainfall (1200-1400 mm) in AES 4 that contributes to the leaching of bases.

According to Landon (1991), AES 4 and AES 3 ranged as strongly acidic, and AES 5 was moderately acidic soil attributed to variations in soil type and microclimate. Similarly, Teferi et al. (2016), who conducted the study in the Blue Nile Jedeb watershed, also reported that the mean pH value of the two agroecological zones (upper and midland) showed strongly acidic soil in the study area. The study by Al Alwani & Al-Shaye (2019) also showed that the soil's original material determines the pH of the soil, the type of vegetation, and the climate (especially the amount of precipitation).

Regarding the main effect of topo-sequence on soil acidity, a significant mean difference was found in the lower slope to the middle slope (mean difference = 0.698) and lower slope to the upper position of the watershed (mean difference = 0.755). The result suggests that pH increases as the slope of the landscape decreases. The lowest pH in the soils of the upper landscape position might be because of the loss of exchangeable bases caused by runoff and erosion and accumulated on the lower slope. These conditions increase the activity of hydrogen ions in the soil and reduce the soil pH. Studies by Bufebo et al. (2021), Dessalegn et al. (2014), and Miheretu & Yimer (2018) are like the current study, which reported that the mean value of soil pH is higher in the lower slope position than in the upper landscape. However, the study contradicts previous studies by Amuyou & Kotingo (2015), which showed a relatively high soil pH value in the upper slope segment compared to other parts of the catena. Mengistu et al. (2016) found a non-significant variation in soil pH among landscape positions. This contradiction could be attributed to variations in climatic conditions in the areas. Without appropriate soil and water conservation measures in this area, acidity might cause soil degradation, and sustainable crop productivity will be affected later.

3.4.3 Available phosphorus

MANOVA showed that available P varied substantially with AES and landscape position and the interaction effect of AES and landscape position (AES*topo-sequence), with an effect size of 67%, 45%, and 56%, respectively (Table 3.5). The two factors' significant interaction effect suggests that the landscape position's effect on available P depends on the AES of the Choke Mountain watershed. According to the Woreda's development agents, in each AES of the Choke, the farming system and input usage, including the application of DAP fertilizer, are different, determining the concentration of available P in the different topographic positions In addition, the topographic positions of each AESs also have a substantial effect on available P that might contribute to the strong interaction effects. AES affected by the soil's acidity (AES 3 and AES 4) recorded the lowest mean value of available P (3.0 mg kg^{-1} and 3.18 mg kg^{-1}), respectively (Table 3.6). The result came from the positive correlation between soil pH and available P (r = 0.568) (Table 3.3). Al Alwani & Al-Shaye (2019) also reported that soil pH affected available nutrients, especially phosphorus.

A significant mean difference in available P was observed among the AES of the watershed. Soil with > 25, 18-25, 10-17, 5-9, and < 5mg kg^{-1}, according to FAO (1980) available P ratings, is classified as very high, high, medium, low, and very low, respectively. Only AES 1 of the Choke has medium available P, whereas AES 4 and AES 5 have low available P, and AES 2 and AES 3 have deficient available P, according to these rates. The very low rate of available P was assigned to the middle landscape positions.

The lower and upper parts of topo-sequences have a low rate of available P (Table 3.1). Earlier researchers like Aytenew (2015) concluded that the variation of available P is highly associated with the variation of organic matter content in each slope gradient. However, the result showed that the available P content of soils did not decrease with a decrease in organic matter. Furthermore, Fe and Al compounds, particularly in clay minerals and metal oxides, have a high adsorption capacity for phosphorus. They can attract and hold phosphorus ions on their surfaces. This adsorption process limits the movement and availability of phosphorus in the soil solution, making it less accessible to plant roots. In contradiction to these findings, available P was not statistically significant, along with the various landscape positions (Amare et al., 2013; Anwanane et al., 2017; Mengistu et al., 2016).

3.4.4 Organic matter

The result shows that OM concentration increased from the Abay gorge's lowlands to the Choke watershed's mountainous highlands. In agreement with this study, Abebe et al. (2020), Ebabu et al. (2020), and Kidanemariam et al. (2012) reported higher OM content in higher altitudes than in lower elevations. Teferi et al. (2016) stated that the higher content of OM was in the middle part of the Jedeb watershed compared to the upper part of the area, which was attributed to different rates of SOM decomposition in the upland and midland of the watershed. According to the rating system established by Tadesse (1991), the OM content of AES was categorized as low (AES 1 & 2), medium (AES 3 & 4), and high (AES 5).

Although the effect size was small based on Cohen's (1988) table, the topographic position also affects the distribution of SOM content in the Choke watershed. In line with this result, Amare et al. (2013), Bufebo et al. (2021), and Miheretu & Yimer (2018) reported the significant effect of landscape position on OM in their study area. The highest mean value of OM is concentrated in the upper position of the AES. The lowest mean value was on the middle slope, followed by the lower slope of the watershed (Table 3.1). Contrary to this study, Jendoubi et al. (2019) reported that higher OM was observed in the lower landscape because of erosion and deposition and lower SOM concentration in the upper position of the Mediterranean landscape. Besides, Aytenew (2015) found that the minimum OM was recorded in sloping and moderately steep soils. In contrast, the maximum OM was recorded in the soils of the gently sloping area. The effect of the slope gradient on the soil moisture storage capacity and biomass production, which is high in gently sloping areas, could contribute to the variation.

The difference in soil OM across the five AES and three landscape positions in the watershed could also be responsible for the local climate, land use, land management, and dominant soil type of the specific area. In line with this study, Abate et al. (2016) also show that the most probable sources of variation in SOM content among the land units might be variations in altitude, the intensity of cultivation, cropping system, and soil management practices. The low temperatures (7.5°C to 10°C) of Choke AES 5 slow down the decomposition of SOM and create conditions of poor aeration (slow oxidation) (Bewket & Stroosnijder, 2003). The high temperature prevailing in AES 1 and AES 2 of Choke handles the rapid burning of OM, thus resulting in the low content of OM in those areas. Regarding land use and farming, intensive cultivation was practiced in AES 2 of Choke with high utilization of inorganic fertilizer but not in AES 5, which is inappropriate for high-intensity agriculture. In addition, in AES 5 of Choke, most farmers use organic fertilizer instead of chemical fertilizer as their local agricultural development agent. This shows that using organic materials helps enhance the soil's organic content, which will help to improve soil quality.

The study on AES analysis of the Choke Mountain watershed by Simane et al. (2013) showed that extensive areas of a vertisol characterize AES 2. The dominant soil type in the Choke watershed's AES plays a significant role in the concentration of OM. Such soils are prone to severe waterlogging (soil compaction) during the rainy season. Although the BD of the soil was not significant in topo-sequence, agroecosystem, and their interaction effect, the highest (1.4 g cm^{-3}) value of bulk density was found in AES 2. The lowest BD was recorded in AES 5 (0.7 g cm^{-3}), showing the effect of soil compaction on OM in the study area. Pearson correlation coefficients also revealed a significant negative correlation between OM and BD (r = -0.688) (Table 3.3).

Similarly, studies conducted in the southern Mediterranean highlands of Turkey reported that high OM in the soil makes it lose and porous, reducing its bulk density (Celik, 2005). Thus, the study suggests a proper technology that will prevent waterlogging and improve drainage in AES 2. Reducing tillage intensity and applying integrated, multifunctional cropping rotations that include forage legumes and small grains will improve SOM and soil quality.

3.4.5 Cation exchange capacity

The soil CEC was insignificant in the topo-sequence and interaction effects (topo-sequence* AES). However, the variation of CEC was statistically significant with a large effect size of (η^2= 0.66) across the five AES of the Choke watersheds. The highest mean value of CEC was found in AES 2 (Table 3.1), where the dominant soil type was vertisol, which is valuable for cultivation. However, the major problems with this soil are low OM content and soil compaction (waterlogging). In agreement with this study, Assefa (2015) also found Vertisols of Gimbichu Woreda in the Oromia Region, which is level to gently sloping, has high CEC and nutrient availability but with the most severe problems of poor drainage, low OM, and total nitrogen. Landon (1991) states that topsoil with a CEC of > 25, 15-25, 5-15, and < 5 meq/100g is classified as high, medium, low, and very low. Based on these ratings, the mean value of CEC in all AES of the Choke watershed is categorized as high. Soil texture is one parameter significantly influencing CEC values (Tomašić et al., 2013). The textural classes of AES of the watershed soils vary from clay, clay loam, and loam to land use and management practice, topographic positions, parent materials, and clay minerals. Clay and OM are also the primary sources of soil CEC and are controlled by them (Aytenew, 2015; Rezaei et al., 2015).

Therefore, the distribution of CEC in different AES of Choke should be followed by clay and OM distribution patterns. The result, however, does not show a similar distribution pattern to clay. The Pearson correlation coefficient revealed that the CEC of the soil was negatively and significantly correlated with the clay content of the soil (r = -0.333) (Table 3.3). This occurs because of other factors, such as the dominance of specific clay minerals, can influence the overall relationship between clay content and CEC. One key factor is the nature of clay minerals present in the soil. Different types of clay minerals have varying cation exchange capacities. For example, some clay minerals, like smectite, have a higher CEC, while others, like kaolinite, have a lower CEC. When soils with higher clay content have a dominance of clay minerals with lower CEC, it can lead to a negative correlation between clay content and CEC. In such cases, the high clay content itself does not necessarily imply a high CEC due to the specific composition of clay minerals present. However, the results contradicted the results of Guteta & Abegaz (2017); Aytenew (2015); and Yitbarek et al. (2013), who reported a positive and significant correlation between CEC and the clay content of the soil.

3.5 Conclusion

The minimum datasets from fourteen soil quality indicators were selected using PCA. Silt content of the soil, soil pH, available P, OM, and CEC were selected as an MDS to evaluate the interaction and main effects of the AES and topo-units on selected soil quality indicators. The interaction of AES and topo-sequence (AES*topo-sequence) affects soil silt content, pH, and available P, showing the impact of one independent variable depends on the other. The silt content of the soil was highest in the upper part of AES 5 and lowest in the lower position of AES 2, which indicates the variation also occurred within the AES. The upper position of AES 3 in the watershed was strongly acidic, attributed to leaching off base ions. AES 1 in the lower part recorded the highest pH mean value, slightly alkaline soil. A similar result was observed for available P, showing a positive correlation with soil pH.

Soil quality indicators varied along with topo-units and across the five AES of the Choke Mountain watershed. Both AES and topo-unit uniquely affected the OM content of the soil, being higher in AES 5 and lower in AES 1. The variation might be attributed to climate, farming system, land use, land cover, and management practices, especially the tillage intensity across the five AES. The soil's CEC was relatively higher in AES 2. However, all AES were still under the higher range of CEC. This finding suggests that farmers should be given suggestions for soil management and agronomic practices based on AES and consider specific topographic regions. As a result, for acid soils, calcium carbonate liming is recommended to boost agricultural production. Reduced tillage intensity and integrated, multifunctional agricultural rotations that contain forage legumes will increase SOM and improve soil quality and the environment for soils afflicted by soil compaction and low OM content.

CHAPTER FOUR

4. SOIL QUALITY INDEX UNDER DIFFERENT LAND USE TYPES: THE CASE OF CHOKE MOUNTAIN AGROECOSYSTEMS, UPPER BLUE NILE BASIN, ETHIOPIA

Abstract

In an agroecosystem (AES), land use types affect soil quality. As a result, determining soil quality in various land uses is critical. This study was carried out to evaluate the soil quality index (SQI) of the different land use types in agroecosystems of the Choke Mountain watershed, upper Blue Nile Basin. Forty-seven soil samples were taken from cultivated land (CL), grazing land (GL), plantation forest land (PFL), and natural forest land (NFL) of the five AES. The minimum data set (MDS) was chosen using principal component analysis (PCA) method. To calculate SQI, five soil quality indicators were selected as an MDS namely: silt, pH, cation exchange capacity (CEC), exchangeable potassium (Ex. K), and soil organic matter (SOM). SQI for the overall land uses was ordered as GL > NFL > PFL > CL. Compared with NFL, the SQI of PFL and CL were reduced by 10% and 19.7%, respectively, whereas the SQI of GL was increased by 1.8%. Among AESs of Choke, SQI of GL was higher in the midland plain, dominated by Vertisol (AES 2), followed by the midland plain with Nitosols (AES 3). SQI of CL was intermediate, and SQI of GL, NFL, and PFL was found good. AES 2 of the watershed recorded the highest total SQI value, whereas hilly and mountainous highlands (AES 5) recorded the lowest SQI compared to other AESs. Thus, site-specific land use and management practices across the various AES should be recommended to policymakers and farmers for a sustainable ecosystem and environment.

Keywords: *soil quality property, principal component analysis, minimum data set, linear scoring, indicator weight, Choke watershed*

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4.1 Introduction

Soil is the base for nearly all land uses, and increasing population pressures and human demands for services from a set of surface areas are severely increasing. This trend threatens and degrades the standard and, therefore, the natural regulating functions of the water, air, and soil resources on which the sustainability of all life forms depends (Dissanayake & Sumanasekara, 2017). Soil degradation could be a global problem in the twenty-first century, particularly in the tropics and subtropics (Lal, 2015), which involves physical, chemical, and biological degradation (Dagnachew et al., 2020). Soil physical degradation refers to a soil's susceptibility to compaction, water-logging, and leaching away. The soil's chemical degradation shows acid and salt soil, leaching, and depletion of a necessary plant nutrient. The lack of soil organic carbon (SOC) and fauna reflects the soil's biological degradation (Lal, 2015). Combining many such degradation results in ecological degradation (Lal, 2015), affecting soil quality's ability to function appropriately and supporting plant and animal survival without threatening the environment (Andrews et al., 2004).

Soil quality is defined as "*the capacity of a selected soil to function, within natural or managed ecosystem boundaries, sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation*" (Karlen et al., 1997). Soil quality is a combination of inherent and dynamic soil properties where inherent soil quality could be a soil's capacity that doesn't change within a brief time. Dynamic soil quality is how soil changes by management practice, where the consequences of management will either end in a net positive or negative impact on the standard of the soil (De La Rosa & Sobral, 2008). Soil quality is significantly affected by improper land use and soil management, deforestation, overgrazing, and other natural variables such as unpredictable and erosive rainfall and steep topography (Kalu et al., 2015). The degraded soil quality has threatened agricultural productivity and a healthy environment globally, particularly in developing countries like Ethiopia, where agriculture is the primary source of economic activity (Lal, 2015).

Unsustainable and sedentary farming practices would negatively affect soil quality, showing that land use and land cover types play a typical role in soil quality. The conversion of forest to cultivated land in Ethiopia's highlands may affect the soil's ability to offer ecosystem services (Delelegn et al., 2017; Kitila et al., 2018; Simane et al., 2013). Farmers in Ethiopia, particularly those in the East Gojjam Zone, plant massive numbers of eucalyptus on small parcels of land and manage them to create a variety of goods and services. Eucalyptus affects soil nutrients, soil erosion, climate, and the water cycle from an ecological standpoint (Amenu, 2017). When eucalyptus stands are harvested, much of the nutrients stored in the aboveground biomass are lost (Amenu, 2017; Mengistu et al., 2016). On the other hand, Adebo et al. (2018), a study showed that the soil quality of plantation forests has significant soil improvement compared to arable land, which reduces SOM and land productivity because of continuous cropping.

Similarly, local community members identified soil erosion in the Choke Mountain watershed as a priority. Although traditional land management, including appropriate agricultural practices and sound forestry practices, has extensively protected the Choke from accelerated erosion in the past, today's land abandonment and forest mismanagement have exploded the frequency of intensive soil erosion events (Simane et al., 2013). Steep slopes, traditional crisscross ox-drawn tillage systems that promote rapid erosion, and limited agricultural land use characterize the Choke environment. Moreover, there is high population growth in the area, leading to the expansion of cultivation of marginal lands of up to 3,800 masl and new human settlements of up to 3,600 masl in the mountain area.

Thus, the association between land use and soil quality should be conceptualized and understood. Assessing the process, characteristics, and mechanisms of soil quality evolution under various land use types and management is a platform for building a scientific soil quality control system and enhancing land management levels (Liao et al., 2015). Understanding changes in soil quality as a function of land use and land management strategies is critical because it gives information on the efficacy of various land use options. As a result, land management strategies must vary as needed to preserve or improve soil quality for long-term land usage (Teferi et al., 2016). Thus, maintaining and improving soil quality is critical, as it has economic and environmental benefits (Ghimire et al., 2018).

On the other hand, individual soil indicators may not be sufficient for determining soil quality (Amacher et al., 2007; Andrews et al., 2004). Doran & Parkin (1994) and Raiesi (2017) show that it is difficult to measure soil quality directly and inferred by measuring soil's physical, chemical, and biological properties. Soil quality index (SQI), the integration of soil quality attributes, is critical for the long-term use and sustainable management of soil resources site-by-site. Thus, soil's physical, chemical, and physical qualities are considered when computing the soil quality index (SQI).

Few studies (Delelegn et al., 2017; Erkossa et al., 2007; Gelaw et al., 2015; Mulat et al., 2021; Tesfahunegn, 2014) applied SQI to quantify the proper indicators for evaluating and monitoring soil quality in Ethiopia. However, extrapolating findings from other studies to the Ethiopian highlands' complex agroecosystem - which has different characteristics in terms of climate, topography and farming system, and soil type- could produce mixed results. Since indicators are purpose and site-specific, variables employed elsewhere may not applied to another location (Shukla et al., 2006). Further attempts have been needed to generate a minimum data set and evaluate the soil quality index among agroecosystems' different land use types.

Therefore, this study aimed to select a minimum data set (MDS) of soil quality indicators using PCA. Thus, MDS help to evaluate the soil quality of different land use types using the soil quality index among agroecosystems of Choke, upper Blue Nile Basin, of Ethiopia.

4.2 Materials and Methods

4.2.1 Soil samplings procedures

The topographic map was used to identify the initial land use and slope class to assign a tentative sampling site. Before collecting the data, general field visual observation, informal discussion, and a survey by transect walk, with the help of the area map, were carried out to merge and determine representative sampling sites. Other relevant information was gathered from different sources, including the district agriculture bureau and development agents. Sample sites from four land use types (CL, GL, PFL, and NFL) across five AES of the Choke Mountain watershed were fixed (Table 4.1).

Forty-seven soil samples were taken from the selected land use types across AESs based on their spatial distribution. Five sub-samples with an "X" plot design with a 10m by 10m plot size were collected from 0-20cm depth and mixed to form a composite sample. Each composite soil samples were mixed, then reduced to 1 kg, and bagged with plastic bags for laboratory analysis. An undisturbed core soil sample was also proportionally sampled using a sharp-edged steel cylinder (core sampler) from the surface soil for bulk density analysis (BD). The top 20 cm of soil is employed in this study because it responds to changes in land use and is prone to soil loss (Abegaz et al., 2016; Tesfahunegn, 2016). Unwanted objects (dead plants and animals, and organic piles) were removed from specific samples and avoided sampling from sediment deposits and field furrows to reduce outlier results.

Table 4.1 Description of land use type classes identified in the study area

Land use type	Description of land use type
Cultivated land (CL)	It is land used by temporary plants that perform their entire life cycle, from germination to harvest, within a single cropping season.
Grazing land (GL)	Land allocated for animals is dominated by grass with scattered bushes.
Plantation of forest land (PFL)	The area is covered by plantation forest (eucalyptus)
Natural forest land (NFL)	The vegetation is densely forested and grows naturally with little human interference.

4.2.2 Soil quality index computation

Indicator Selection: The convenience and expense of sampling, the impact on soil productivity and sensitivity to environmental changes, and the analysis method of the selected variables were all factors in selecting soil quality indicators (S. S. Andrews et al., 2002; Doran & Parkin, 1994)(Doran & Parkin, 1994). Using SPSS version 26.0, each soil's original observations (untransformed data) were incorporated into the PCA model. Under each PC, highly (> 0.7) weighted variables (Teferi et al., 2016; Tesfahunegn & Gebru, 2020b) were selected as soil quality indicators. Corellinerity analysis was used to check for redundancy (Andrews et al., 2004; Vasu et al., 2016). The variables with the highest factor loading (absolute value) were retained as an MDS if the variables were well-correlated (r > 0.60) (Filep et al., 2016; Mukherjee & Lal, 2014; Sánchez-Navarro et al., 2015; Tesfahunegn & Gebru, 2020b).

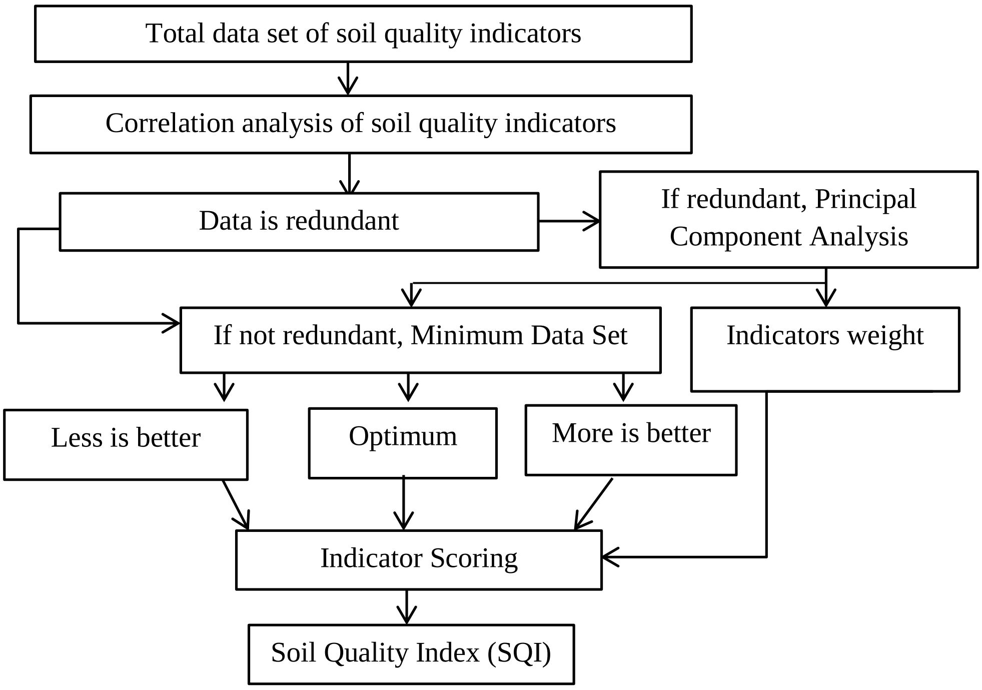

Figure 4.1 Flow chart of soil quality index computation

Indicator transformation: The next step involved transforming or scoring the observed indicator value using a linear transformation method. The linear scoring method is often straightforward and easy to understand. It involves assigning scores or ratings on a linear scale, typically ranging from 0 to 1. In the linear scoring system, each indicator is classed as "more is better," "less is better," or "optimum" (Armenise et al., 2013). In the "optimum is better" scenario, indicator observations are rated as "more is better" until they reach the threshold level, at which point they are scored as "less is better" (Andrews et al., 2004; Jiang et al., 2020). To normalize each indicator into a standard range between 0 and 1, two linear equations (Equations 1 and 2) were used.

$$Si = (Xi - Xi,min)/(Xi,max - Xi,min) \quad (1)$$

$$Si = (Xi,min - Xi)/(Xi,max - Xi,min) \quad (2)$$

Where *S* is the indicators score for each variable *i*, *X* is the value of the soil quality indicators *i*; maximum and minimum values of i^{th} soil quality indicators, respectively, are represented by max and min. Equation (1) is for the "more is better" function; equation (2) is for the "less is better" scoring function.

Integration into an Index: Following that, each kept indicator is weighted depending on PCA results. Each PC explained a specific percentage of the variation in the overall data set. The weight factor (W) for indicators chosen under a specific PC was the percentage of variance explained by all PCs with eigenvalues >1, divided by the total percentage of variation (Filep et al., 2016). The weighted indicator scores were summed together for each observation using equation (3) (Andrews et al., 2002).

$$SQI \quad = \sum_{i=1}^{n}(Wi \times Si) \qquad (3)$$

Where *SQI* is the soil quality index, W_i is the weighting factor for the indicator i calculated from PC, and S_i is the score of selected MDS. The SQI was divided into five categories: very high (> 0.80), high (0.60-0.80), medium (0.40-0.60), low (0.20-0.40), and very low (<0.20) (Ghimire et al., 2018; Liao et al., 2015; Tadesse, 2021). The soil with a higher index score based on the above criteria has better soil quality, and soil quality indicators function better.

4.2.3 Statistical analysis

Normality distribution was tested with the Shapiro-Wilk test of a standardized variable to proceed with further analysis. A logarithmic transformation was applied used to normalize non-normally distributed data. PCA was performed on the soil quality parameters, meeting the preliminary assumption to examine the relationship among the variables by statistically grouping them into principal components. Then the PCs with eigenvalue over one (1) were kept and selected for further analysis (Andrews and Carroll, 2001; Kaiser, 1960; Rezaei et al., 2006).

Sampling adequacy was tested through Kaiser-Meyer-Olkin (KMO) (Kaiser, 1974) in SPSS. The sampling is appropriate if the KMO test value is over 0.5 (Kaiser, 1974, Kaiser, 1970). The sphericity test devised by Bartlett determines the strength of an association between variables. Small values (< 0.05) of the significance level show that factor analysis may be helpful in data (Bartlett, 1954). The soil quality index under different land uses, and agroecosystems was subjected to the ANOVA statistics. The General Linear Model (GLM) techniques in SPSS were used to complete all the tasks (Ver.26).

4.3 Result

4.3.1 Measured soil quality indicators

For the present study, fourteen properties of physical, chemical, and biological soil quality attributes were measured and analyzed (Table 4.2). The average value of the soil quality parameters varied across agroecosystems of the Choke Mountain watershed and land use types. The selection of soil quality indicators is based on several factors and considerations including sensitivity and responsiveness, feasibility and practicality and scientific validity.

Table 4.2 Descriptive statistics of all the measured soil quality indicators on Choke (n = 47 except BD, where n = 36)

Soil Quality Indicators	Minimum	Maximum	Mean	SD[8]
Silt (%)	11.00	43.00	25.71	8.26
Clay (%)	18.00	75.00	52.55	15.29
BD (g cm^{-3})	0.70	1.40	1.01	0.13
Porosity (%)	47.00	74.00	61.76	4.82
pH (H_2O)	4.62	8.05	5.95	0.91
CEC (meq/100g)	22.17	59.47	39.32	10.37
Ca (cmol kg^{-1})	0.00	57.63	15.98	16.27
Mg (cmol kg^{-1})	0.00	16.59	6.58	4.55
Ex. Na (cmol kg^{-1})	0.00	0.30	0.06	0.06
Ex. K (cmol kg^{-1})	0.20	3.33	0.79	0.64
PBS (%)	0.76	139.02	53.31	38.56
OM (%)	1.13	13.66	4.95	2.90
TN (%)	0.07	0.77	0.28	0.16
Av. P (mg kg^{-1})	1.34	40.00	6.67	6.48

Note: BD, bulk density; CEC, cation exchange capacity; Ca, calcium; Mg, magnesium; Ex. Na; exchangeable sodium; Ex. K, exchangeable potassium; PBS, percent base saturation; OM, organic matter; TN, total nitrogen; Ava. P, available phosphorus

4.3.2 Minimum data set selection

To define the minimum data sets for soil quality evaluation, a PCA was performed on the 14 soil quality parameters. The Kaiser-Meyer-Olkin (KMO) metric, KMO = 0.639, showed that the sampling adequacy for factor analysis exceeded the acceptable limit of 0.5. The corresponding *P* value for Bartlett's test of sphericity was less than 0.01, which was very

[8] Standard Deviation

significant (2 (91) = 735.162, *p* = 0.000), justifying the continuation and correct factor analysis.

In the principal component analysis, 14 soil quality indicators were divided into components, and four components were kept as their eigenvalues exceeded the Kaiser's threshold of 1, explaining 85.09% of the total variance in the entire data set (Table 4.3).

The first PC 1 accounts for 36.03% of the total variance with high loadings (> 0.7) variables, including pH, CEC, Ca, Mg, and PBS (Table 4.3). PC 1 was identified as a "nutrient availability" component. The second PC explained 25.75% of the variance with high loadings variables (BD, porosity, OM, and TN) and was identified as a "root penetration and nutrient retention" component. Component-3 accounted for 15.13% of the total variance with high loadings from clay and soil silt content and was named as "soil texture component". With strong loading from exchangeable K and available P, component 4 explained 8.16% of the overall variation. PC 4 was designated as a "major nutritional component" since it is one of the most essential" nutrients for plant growth.

Table 4.3 The factor loadings after Varimax rotation and communality estimates

	PCs[9]				
Soil quality indicator	PC 1	PC 2	PC 3	PC 4	Communality
Clay (%)	-0.014	-0.304	**-0.915**	0.041	0.932
Silt (%)	0.013	0.237	**<u>0.889</u>**	-0.064	0.851
BD (g cm^{-3})	0.134	**-0.881**	-0.099	-0.235	0.859
Porosity (%)	-0.13	**0.883**	0.107	0.249	0.87
pH (H_2O)	**<u>0.833</u>**	-0.269	-0.032	0.256	0.832
CEC (meq/100g)	**<u>0.825</u>**	0.219	0.277	-0.173	0.836
Ca (cmol kg^{-1})	**0.959**	-0.119	0.03	0.065	0.939
Mg (cmol kg^{-1})	**0.903**	-0.187	-0.182	0.049	0.885
Ex. Na (cmol kg^{-1})	0.531	0.233	-0.277	-0.562	0.728
Ex. K (cmol kg^{-1})	0.099	0.173	-0.155	**<u>0.865</u>**	0.812
PBS (%)	**0.906**	-0.215	-0.039	0.228	0.92
OM (%)	-0.113	**<u>0.771</u>**	0.494	-0.081	0.858
TN (%)	-0.099	**0.786**	0.41	-0.123	0.811
Av. P (mg kg^{-1})	0.275	0.169	-0.054	0.821	0.781
Eigenvalue	5.045	3.606	2.119	1.143	
Variance (%)	36.037	25.755	15.132	8.166	
Cumulative (%)	36.037	61.792	76.925	85.091	
Weight	0.424	0.303	0.178	0.096	

[9] Principal components

Note: BD, bulk density; CEC, cation exchange capacity; Ca, exchangeable calcium; Mg, exchangeable magnesium; Ex. Na, exchangeable sodium; Ex. K, exchangeable potassium; PBS, percent base saturation; OM, organic matter; TN, total nitrogen; Ava. P, available phosphorus; MDS, minimum data set. Factor loadings > 0.7 appear bold, and the underlined variables were kept as MDS

Two highly weighted variables (pH and CEC) from PC 1 were not well-correlated (r =.522) (Table 4.4) and were maintained as MDS. OM was well-correlated with the other variables from PC 2, and OM was chosen as an MDS since it was the only biological indicator for this investigation, although porosity had the highest factor loading from PC 2. The soil content of clay and silt had a significant correlation (r = -.905) in PC 3, and only silt was preserved as an MDS because clay strongly correlates with OM (Table 4.4).

Finally, from PC 4, the exchangeable k with the largest factor loading was chosen. As a result, the variables with the highest absolute value factor loading (silt, pH, CEC, OM, and exchangeable K) were kept as the MDS from the four PCs to calculate SQI for CL, GL, PFL, and NFL for the AES of Choke Mountain watershed.

Table 4.4 Pearson correlation coefficients for soil quality indicators (n = 47, except BD, n = 36)

SQ indicators	Silt	Clay	BD	Porosity	pHH2O	CEC	Ca	Mg	Ex. Na	Ex. K	PBS	OM	TN	Av. P
Silt (%)	1	-.905 [b]	-.331 [a]	.336 [a]	-0.071	.297 [a]	-0.003	-0.097	0.069	-0.12	-0.041	.557 [b]	.478 [b]	-0.003
Clay (%)		1	.366 [a]	-.371 [a]	0.077	-.336 [a]	-0.008	0.069	-0.01	0.075	0.051	-.660 [b]	-.595 [b]	0.041
BD (g cm^{-3})			1	-.998 [b]	0.215	-0.018	0.198	0.318	0.059	-0.245	0.206	-.609 [b]	-.599 [b]	-0.209
Porosity (%)				1	-0.206	0.018	-0.194	-0.319	-0.066	0.258	-0.2	.619 [b]	.609 [b]	0.223
pH (H_2O)					1	.522 [b]	.890 [b]	.735 [b]	0.277	0.267	.940 [b]	-0.244	-0.245	.298 [a]
CEC (meq/100/g)						1	.768 [b]	.726 [b]	.485 [b]	0.086	.615 [b]	.305 [a]	0.284	0.136
Ca (cmol kg^{-1})							1	.807 [b]	.368 [a]	0.246	.942 [b]	-0.083	-0.09	0.226
Mg (cmol kg^{-1})								1	.535 [b]	0.276	.835 [b]	-0.121	-0.129	0.255
Ex. Na (cmol kg^{1})									1	0.008	.327 [a]	0.163	0.167	-0.074
Ex. K (cmol kg^{-1})										1	.310 [a]	0.068	0.028	.698 [b]
PBS (%)											1	-0.168	-0.184	.318 [a]
OM (%)												1	.975 [b]	0.038
TN (%)													1	0.008
Av. P (mg kg^{-1})														1

Note: BD, bulk density; CEC, cation exchange capacity; Ca, exchangeable calcium; Mg, exchangeable magnesium; Ex. K, exchangeable potassium; PBS, percent base saturation; OM, organic matter; TN, total nitrogen; Ava. P, available phosphorus; MDS, minimum data set. [b] Correlation is significant at the 0.01 level (2-tailed), correlation is significant at the 0.05 level (2-tailed)

4.3.3 Indicator scoring and integrating into an index

A "more is better" curve was used for OM, CEC, and Ex. K., a "less is better" function was used for soil silt content. The "optimum" function was applied to pH H_2O, and points were assigned based on whether the indicator value was below or above the threshold value (7), using equation (1) and equation (2).

Table 4.5 Mean score value of MDS of different land use types of the study watershed (n= 47)

AES	LU	Silt (%)	PH (H_2O)	CEC (meq/100g)	Ex. K (cmol kg^{-1})	OM (%)	$SQI = \Sigma (Wi \times Si)$
AES 1	CL	0.430	0.420	0.360	0.490	0.386	0.571
	PFL	0.500	0.500	0.500	0.500	0.423	0.689
	Total	0.465	0.460	0.430	0.495	0.404	0.630
AES 2	CL	0.443	0.512	0.449	0.500	0.520	0.692
	GL	0.650	0.620	0.526	0.432	0.484	0.789
	PFL	0.500	0.500	0.500	0.496	0.500	0.712
	NFL	0.500	0.500	0.500	0.500	0.541	0.725
	Total	0.523	0.532	0.494	0.481	0.511	0.729
AES 3	CL	0.333	0.361	0.335	0.669	0.353	0.526
	GL	0.667	0.556	0.528	0.371	0.456	0.752
	PFL	0.500	0.500	0.501	0.485	0.500	0.711
	NFL	0.536	0.500	0.550	0.500	0.500	0.740
	Total	0.509	0.480	0.478	0.506	0.452	0.682
AES 4	CL	0.375	0.465	0.520	0.325	0.369	0.628
	GL	0.500	0.500	0.380	0.517	0.500	0.663
	PFL	0.482	0.395	0.399	0.495	0.416	0.596
	NFL	0.510	0.500	0.500	0.520	0.500	0.716
	Total	0.466	0.464	0.449	0.464	0.446	0.650
AES 5	CL	0.386	0.396	0.310	0.300	0.342	0.501
	GL	0.518	0.471	0.523	0.440	0.572	0.729
	PFL	0.500	0.329	0.416	0.328	0.386	0.553
	NFL	0.500	0.500	0.500	0.500	0.530	0.722
	Total	0.476	0.423	0.437	0.398	0.457	0.626
Total	CL	0.393	0.430	0.394	0.456	0.394	0.582
	GL	0.583	0.536	0.502	0.440	0.502	0.738
	PFL	0.496	0.448	0.463	0.461	0.444	0.653
	NFL	0.511	0.500	0.512	0.505	0.517	0.725
	Total	0.497	0.466	0.467	0.466	0.464	0.669

Note: AES, agroecosystem; LU, land use; CL, cultivated land; GL, grazing land; PFL, plantation forest land; NFL, natural forest land; CEC, cation exchange capacity; Ex. K, exchangeable potassium; OM, organic matter; MDS, minimum data set; SQI, soil quality index; Wi, the weight of variables from principal components; Si, a score of the variables.

The integrated index value for soil quality under different land use types was then calculated by multiplying the score by the weighting factor determined by the PCA.

The weighted factor of each PC based on the percent variance to the total variance ranged from 0.096 to 0.424 (Table 4.3). Integration of the soil quality parameter into SQI in a land use type using the framework resulted in order of GL > NFL > PFL > CL, whereas across the Choke Mountain watershed, SQI resulted in order of AES 2 > AES 3 > AES 4 > AES 1 > AES 5 (Table 4.5).

4.4 Discussion

Five (silt content, pH, CEC, Ex. K, and OM) indicators from physical, chemical, and biological attributes were chosen as an MDS to evaluate the SQI of four land use types. Most MDS has been found in prior research (Adebo et al., 2020; Nabiollahi et al., 2018; Teferi et al., 2016; Tesfahunegn, 2014) as essential indicators for assessing soil quality in diverse land use systems. Soil texture (silt) is the fundamental soil physical property controlling exchange, retention, and uptake. It is a master physical feature of soil that improves most other attributes and processes (Schoenholtz et al., 2000). The pH of the soil is a chemical property that should be considered an essential indicator of soil quality (Doran & Parkin, 1994). CEC is a vital soil quality indicator showing whether the land is fertile and can hold and prevent the nutrients from being washed away (Aprisal et al., 2019). Exchangeable K is one of the chemical nutrient availability indicators with specialized scoring functions for plant production and environmental components of soil quality (Cakmak, 2010).

Soil OM is a significant component of several soil biological characteristics (Adebo et al., 2020; Maurício Roberto Cherubin et al., 2017; Glover et al., 2000; Idowu et al., 2008) and plays a crucial role in enhancing soil fertility and ecosystem productivity (Jiang et al., 2020). In many parts of the world, SOM is the most potent indicator for assessing the soil quality index under various land uses and management interventions (Shukla et al., 2006). For this study, SOM was used as a biological indicator, as also used by other researchers (Adebo et al., 2020; Cherubin et al., 2016; Rashidi et al., 2010) because of the lack of accessibility of laboratories for microbial indicators in Ethiopia. Besides, because of the lack of peace and security in the Choke watershed's AES 1, soil samples were gathered only from CL and PFL.

4.4.1 Soil quality index under different land use types

The soil quality of cultivated land

For the cultivated land of the Choke watershed, the results of the integrated SQI were 0.58. The CL use types scored intermediate, according to (Ghimire et al., 2018), but with relatively lower SQI values compared to the other land use types, which might be attributed to the low level of OM owing to the removal of crop residue, and limited addition of manure. The results agreed well with previous studies (Abegaz et al., 2016; Bewket & Stroosnijder, 2003; Gelaw et al., 2015; Mulat et al., 2021; Negasa et al., 2017; Yu et al., 2018a). Low SOC levels also characterize CL because of the removal of substantial amounts of OM through harvesting and the quick decomposition rates induced by frequent and long-term tillage activities (Ebabu et al., 2020). The decreased plant biomass input and increased human disturbance were linked to lower soil quality under the CL treatment (Raiesi, 2017; Yu et al., 2018a). The SQI value of CL was reduced by 19.7% compared to the NFL treatment (Table 4.5).

The soil quality index of the CL among the five AES was higher (0.69) in AES 2 of the Choke watershed, followed by AES 4 (0.63). In AES 5, the SQI of CL was low (0.5) (Fig 4.2). The cultivation of steep and fragile soils and limited incorporation of animal dung and crop residues are driving agents for the low SQI of CL in AES 5 of the Choke. Tillage practice in AES 5 is attributed to soil erosion, which leads to nutrient depletion, land degradation, and thereby soil quality deterioration. The result suggests strengthening and expanding fertility management practices such as organic fertilizer (manure, composts) to sustain agricultural production in agroecosystems.

Soil quality of grazing land

As the integrated soil quality result revealed, the SQ of GL (0.74) was better than the other land use types. Compared with the NFL treatment, the SQI values of GL were increased by 1.8% (Table 4.5). It might be attributed to the high mean value of SOM contents because of the high availability of organic fertilizers, like animal manure. Furthermore, animal grazing significantly impacts soil structure, function, and the ability to store nutrients (Abdalla et al., 2018). Thus, highly interrelated variables of high SOC, SOM, and TN and low BD yielded high SQI in the GL of the watershed. The result contradicts Adebo et al. (2020) and Yu et al. (2018), who found that GL's SQI was less than NFL soil quality.

Along with the Choke watershed, the SQI of GL was higher in AES 2 (0.79), followed by AES 3 (0.75). The soil in AES 2 of the Choke watershed is a vertisol and productive type of soil. SQI for GL was low in AES 4 compared to others (Fig 4.2). It is attributed to the degraded land because of erosion and leaching of bases.

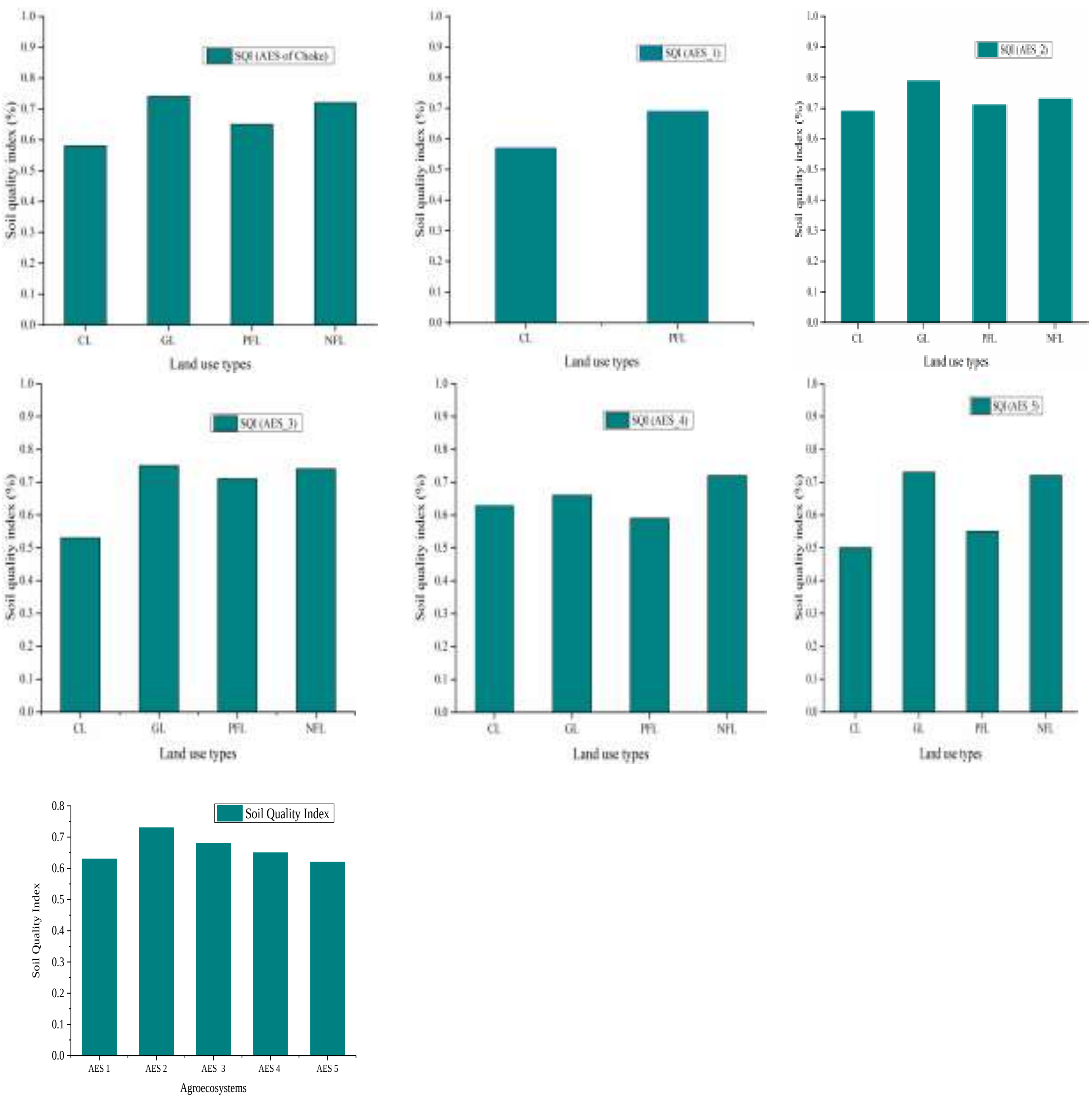

Figure 4.2 Soil quality index of land use types within and across the watershed

Note: AES, agroecosystem; AES 1, lowland and valley fragmented; AES 2, midland plain dominated by Vertisol; AES 3, midland plain with Nitosols; AES 4, sloppy midland land; AES 5, hilly and mountainous highlands; SQI, soil quality index; CL, cultivated land; GL, grazing land; PFL, plantation forest land; NFL, natural forest land

The soil quality of eucalyptus plantation forest

The SQI value of PFL in the Choke was 0.65 and reduced by 11.5% compared to the value of GL. Bewket & Stroosnijder (2003), in the Chemoga watershed, Blue Nile Basin, also found that the soils under eucalyptus plantations had the poorest soil quality, although the coverage has been increasing since the 1950s. This shows that the tree has been planted in already degraded lands and is poor at restoring soil fertility. In addition, harvesting planted forests (deforestation) regularly is a common practice that some residents of the area have become dependent on it for their livelihood, which can reduce SQI. Mengistu et al. (2016) confirm a substantial loss of soil nutrients in plantation forests after harvesting first coppicing.

Among the five AES of Choke, SQI of PFL failed under medium-class and was relatively lower at AES 5 (0.55) and AES 4 (0.59) of the watershed. It might be attributed to the high leaching of bases because of the high mean annual rainfall (1200-1400mm) in both AESs. According to Landon's (1991) rating, the PFL of these AES has also been strongly acidic, recording the lowest mean value of pH (5.01 for AES 4 and 5.41 for AES 5), which might reduce SQI. In AES 4, the SQI of PFL was reduced by 5% compared to the CL of the area. Thus, plantations of eucalyptus effects on soil quality may not always be beneficial, as shown by (Teferi et al., 2016). The results disagree with Adebo et al. (2020), a study in Nigeria that showed that the SQI of arable land was lower than PFL because of continuous cropping and other unsustainable practices, which reduce SOM and land productivity. However, in the remaining AESs, SQI of PFL was increased by 17%, 2.8%, 26%, and 9.4% in AES 1, AES 2, AES 3, and AES 5, respectively, as compared to the CL system (Table 4.5).

The soil quality of natural forest land

The SQI value of NFL was reduced by 1.8% compared to GL across the watershed. SQI of NFL across the AES of Choke was almost equal (with a range of 0.72-0.74), and no significant difference among them. A study of soil quality in various land use types in Shiqu, China, came to the same conclusion (Liao et al., 2015). A study conducted by Jiang et al. (2020) also found soil quality value of natural forest land was lower than even the agricultural land in the study area. But the result was contradicted by another study (Yu et al. (2018a), where the soil quality of NFL was better than other land use types. The Choke watershed has no significant natural vegetation cover and is seen sparsely. Some human disturbance in the natural forest might also reduce soil quality.

4.4.2 Soil quality index across AES of Choke watershed

The order of SQI among AESs of the Choke was AES 2 (0.73) > AES 3 (0.68) > AES 4 (0.65) > AES 1 (0.63) > AES 5 (0.62) (Fig 4.2). Although the concentration of OM was high in AES 5 of the watershed, SQI is low compared to other AES, showing that individual soil quality indicator does not determine the soil quality of the area. It might be attributed that the area is hilly and mountainous, with an altitude ranging from 2800-3800 masl and rainfall ranging from 1200-1400mm, causing soil erosion and severe soil degradation (Simane et al., 2013) and acidity. Similarly, AES 1 of the watershed, from the lowland of the Abay river up to an altitude of 1400 masl, was affected by landslide and moisture stress (Dmu.edu.et, 2020) and reduced soil quality of the ecosystem. A study conducted on an agroecosystem analysis of the Choke Mountain watersheds by Simane et al. (2013) also shows that fragmented and steep slopes characterize AES 1 and 5 with the highest degradation rate, reducing soil quality.

Following AES 1 and 5, Choke Mountain's midland sloping lands (AES 4) were affected by low natural fertility because of the leaching of basic cations, including Ca, Mg, Ex. K that leads to a high level of acidity. The reason is the terrain is sloping, which is unsuitable for cultivation and other activities and subject to higher rates of soil erosion. AES 3, a midland plains area of the watershed dominated by Nitosols. Deep, well-drained Nitisols are among the most productive soils in the humid tropics, suitable for many crops (Simane et al., 2013). Even though AES 3 of the watershed was affected by soil acidity, it has good chemical (fertility) qualities and has a good soil quality index following AES 2.

All agroecosystems have various problems that reduce soil quality. The integrated soil quality result revealed that the highest soil quality index value was found in AES 2 of the Choke Mountain watershed, dominated by heavily textured Vertisols. This could be because of the high fertility of the soil with a high CEC value and other nutrients. The physiographic setting of the area also contributed to the high SQI of the agroecosystem. However, the content of OM in the area was low, and the highest bulk density was found, which might cause waterlogging. In agreement, Simane et al. (2013) also showed that because of the high content of shrink-swell clay in these soils, cultivation is difficult when dry, and water-logging is a problem when wet. Thus, ecosystem-based management practice should be applied across the various AESs of the Choke watershed, as they are different in soil type, terrain, and farming system.

4.5 Conclusion

The 14 soil physical, chemical, and biological variables were measured to evaluate the soil quality index (SQI) of diverse land use types across the five AES of the Choke watershed. And only silt content of the soil, pH, CEC, Ex. K and SOM were kept in the refined MDS based on the PCA results to compute the soil quality index of land use types across the Choke AESs. SQI for the land uses is ordered as GL > NFL > PFL > CL across the overall watershed. Compared with NFL, SQI values under PFL and CL were reduced by 10% and 19.7%, respectively, whereas SQI of GL was increased by 1.8%. SQI of CL was intermediate, whereas SQI of GL, NFL, and PFL of the overall AES of the Choke watershed was high. Continuous tillage and over-addition of fertilizers on the cultivated land decreased SQI in the AESs of the Choke watershed. Among AES of Choke, SQI of GL was higher in AES 2, followed by AES 3. However, in AES 4, higher SQI was found in NFL, and lower SQI was recorded under the PFL of the area. SOM and soil pH were the significant contributors to variation in SQI among the land use systems. The lower value of pH and leaching of bases were a reason for the lower value of SQI of PFL in AES 4 of the watershed. AES 2 of the watershed recorded the highest total SQI value, whereas AES 5 recorded the lowest SQI compared to other AES of the Choke watershed because of the steepness of the area and vulnerability to soil erosion.

Thus, site-specific land use and land management practices across the various AES should be recommended to land managers and farmers for the sustainability of AES. Further study is suggested to study the effect of eucalyptus forests on the soil as it degrades, improves, or maintains soil quality at various agroecosystems.

CHAPTER FIVE

5. FARMERS PERSPECTIVES AND SCIENTIFIC-BASED ASSESSMENT OF SOIL QUALITY IN THE UPPER BLUE NILE BASIN, ETHIOPIA

Abstract

Local farmers' expertise in soil quality and management strategies is essential for maintaining the soil fertility of farmlands through inclusive indigenous knowledge management strategies to sustain farm productivity. Therefore this study aims to investigate farmers' and scientific-based assessment of soil quality in the Upper Blue Nile Basin, Ethiopia. To achieve this objective, one hundred twenty-three households were selected purposively from the five agroecosystems (AESs) of the Choke watershed and interviewed concerning view of their land fertility. In addition a total of 20 composited soil samples were taken from 0 - 20 cm soil depth from plots of surveyed farmers. The results demonstrated a relationship between local farmers and scientific soil quality assessment indicators. Perceptions and views of farmers regarding soil quality were based on visible crop performance, soil-related indicators, biological indicators, and the slope of the area. Farmers from the midland part of the watershed perceived a high soil quality with high crop yield with green leaf color, black/dark soil color with good water holding capacity. However, higher nutrients, including soil organic matter, total nitrogen, and available phosphorous recorded in the sloppy and mountainous highlands of the watershed. This shows that there is some inconsistency in the classification of soil quality of agricultural lands by farmers and scientific assessment across the various agroecosystems, which was created by the application of soil and crop management practice. Thus, the result suggested that local soil knowledge should be constructed for the site-specific agroecosystem to sustain soil and crop production.

Keywords*: Farmers' perception, scientific analysis, soil quality indicator, agroecosystem, upper Blue Nile Basin*

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5.1 Introduction

Over the last two to three decades, the agriculture industry's stakeholders have increasingly focused on soil quality and fertility indicators (Andrews et al., 2004). Due to the growing criticism of the traditional top-down model of technology transfer and scientific knowledge for being unsuccessful, research and development paradigms incorporating local farmers' knowledge are receiving much attention (Wawire et al., 2021; Yageta et al., 2019). Farmers have an intimate and well-developed knowledge system about their soils, nutrient provision through the decomposition of organic plant litter, and nutrient loss and cycling processes (Dawoe et al., 2012).

Farmers' perceptions of soil characteristics are based on observation and life experience gained through time and progressively passed down through generations (Wawire et al., 2021). The color and texture of the soil, the slope's location, how the soil interacts with the flora, drainage, hardness, and even odor are all indicators used by farmers worldwide (Bicalho and Peixoto, 2016). Different soil types can be identified by their color and texture, which are related to their degrees of fertility. The soil's acidity can also be determined by its taste, which can be sweet, bitter, or neutral (Bicalho and Peixoto, 2016). Farmers evaluate soil holistically because it results from intricately interconnected environmental factors (Wawire et al., 2021). Thus, a more comprehensive strategy to connect local and scientific information would be applied to support local development (Bicalho and Peixoto, 2016), where the approach is socially acceptable, ecologically sustainable, and economically viable. Also, it is thought to compensate for the limitations of scientific intervention while operating over a broader range (Laekemariam et al., 2017). Ethnopedology is a brand-new research branch created due to the global recognition of farmers' indigenous expertise. The goal of ethnopedology as a subject of study is to record and comprehend regional perspectives on how soil is perceived, categorized, valued, used and managed (Barrera-bassols & Zinck, 2003).

Understanding farmers' perception of soil related to objective soil properties is vital to using knowledge as a resource in the scientific investigation of soil (Gruver & Weil, 2007). Both farmers and scientists have used various techniques to evaluate soil using qualitative and quantitative indices (Laekemariam et al., 2017). Their expertise can provide a wealth of information for sustainable soil management in their specific farm plots. Thus, Farmers' experience, local knowledge, and indigenous practices are necessary resources that should be developed with scientific knowledge. Such a participatory research approach involving farmers is essential for developing technologies and management innovations (Laekemariam et al., 2017). Studies were conducted in different parts of Africa, including Ethiopia (Corbeels, 2000; Laekemariam et al., 2017; Yeshaneh, 2015), Nigeria (Adeyolanu et al., 2018; Obateru, 2022), Kenya (Wawire, Csorba, et al., 2021; Yageta et al., 2019), Ghana (Dawoe et al., 2012; Omari et al., 2018) and Rwanda (Kuria et al., 2019b). Furthermore, Yirgalem (2015) studied the perception of farmers on their soil erosion at the upper part (Sinan Woreda-one agroecosystems of Choke) of the watershed.

Effective collaboration among farmers, scientists, extension agents, and other stakeholders should be crucial in areas with vast agroecosystems like the Choke watershed to develop a practical adaptive soil management technique that improves soil productivity. However, in a complicated physiographic setting like the East Gojjam zone (Choke agroecosystem), applying specific agroecosystems' soil fertility management approaches to another agroecosystem is problematic and unsustainable for soil and crop yield. Thus, although farmers have a more thorough understanding of their soils and management practices, it is better if their knowledge is supported by scientific facts and site-specific (agroecosystem-based) soil data, which are less thoroughly investigated in the Choke watershed.

Therefore, the main objective of this study was to investigate farmers' and scientific-based assessment of soil quality in the Upper Blue Nile Basin, Ethiopia.

5.2 Material and Methods

5.2.1 Data and soil sampling

Social survey

A social survey was conducted using pre-tested semi-structured questionnaires and key informant interviews from December 2020 to Feb 2021, where 123 farmers were purposively sampled from five agroecosystems (AES 1, AES 2, AES 3, AES 4, and AES 5). The selected farmers were predominantly farmers participating in agricultural activities. The criteria for the selection were based on the significant economic activities of the people (in this case, farming). Five (one from each AES) key informants have also participated and asked about their perception of soil quality and indicators that they used to express their soil (land). Pre-tested structured and semi-structured questionnaires were used in the survey to collect data on soil quality and status indicators and classification of soil quality based on indicators. Based on a list of predetermined indicators from the literature review, crop performance, soil characteristics, biological indicators, and topographic factors were asked to describe soil quality as high, medium, and low.

Soil sample procedures and analysis

The soil sample was taken for laboratory analysis to compare the results of farmers' perceptions and scientific analysis of soil. A total of 20 composited soil samples were taken within 0 - 20 cm soil depth from a plot of surveyed farmers purposively. Five sub-samples from each farm were collected to take 1kg of composited soil. The collected soil was well-labeled in plastic bags and sent to National Soil Testing Center, Addis Ababa.

Soil color was described using the Munsell soil color chart. Particle size distribution and bulk density are analyzed to simultaneously see the physical characteristics of soil with farmers' perception. An undisturbed soil sample was taken using a sharp-edged steel cylinder (6 cm long * 6 cm in diameter), and core soil samples were for BD analysis by drying the core samples in an oven at 105°C (Sahlemedhin and Taye, 2000).

5.2.2 Data analysis

By comparing the findings from the soil laboratory analysis and farmers' interviews based on indicators, we gain a broader understanding of the soil quality attributes, identify potential discrepancies or consistencies, and capture valuable local knowledge that may inform future soil management strategies. The survey data were processed and subjected to descriptive statistics such as frequencies, percentages, and mean. The Chi-Squared statistic is used to examine whether there is a difference between the observed and the expected results. The Least Significant Difference (LSD) pairwise comparison of means was used to identify significant differences between the soil quality categories.

5.3 Result

5.3.1 Respondents profile

Of the 123 respondents, 17.1% were females, and 82.9% were males (Table 5.1). The age of the respondents ranged from 22 to 76 years, with an average of 49 years. A significant percentage (44.7%) of the respondents was between 40 and 49. Regarding their marital status, a large number of them are married. About 83.7% are married, and the remaining 16.3% are single, divorced, or widowed. Most (55.3%) of the respondents can read and write without formal education (Table 5.1). On the other hand, only 4.1% had a primary and above education. Furthermore, crop-livestock mixed farming is the primary source of livelihood in the surveyed communities.

There were no significant differences between farmers concerning gender, marital status, educational background, or sources of livelihood (Table 5.1). As a result, demographic similarities between research communities' household characteristics were found among the five agroecosystems, except for the age of the respondents.

Table 5.1 Chi-square analysis of differences in respondents' selected personal and demographic characteristics

Respondent's Characteristics		Agroecosystems of Choke Mountain Watershed						Pearson Chi-Square (χ2)
Description	Categories	AES 1 (N=21)	AES 2 (N=25)	AES 3 (in %) (N=24)	AES 4 (N=23)	AES 5 (N=30)	Total	
Sex	Male	16.3	16.3	17.1	15.4	17.9	82.9	4.706, df=4 *P* = 0.319
	Female	0.8	4.1	2.4	3.3	6.5	17.1	
	Total	17.1	20.3	19.5	18.7	24.4	100.0	
Age	20-29	0.0	0.8	0.8	0.8	2.4	4.9	24.266, df=12 *P* = 0.019
	30-39	1.6	8.1	3.3	1.6	5.7	20.3	
	40-49	7.3	10.6	5.7	10.6	10.6	44.7	
	>=50	8.1	0.8	9.8	5.7	5.7	30.1	
	Total	17.1	20.3	19.5	18.7	24.4	100.0	
Marital status	Single	0.0	2.4	0.0	2.4	0.8	5.7	21.833, df =12 *P* = 0.059
	Married	17.1	16.3	17.9	14.6	17.9	83.7	
	Divorced	0.0	1.6	0.8	0.0	0.8	3.3	
	Widowed	0.0	0.0	0.8	1.6	4.9	7.3	
	Total	17.1	20.3	19.5	18.7	24.4	100.0	
Educational status	Illiterate	1.6	9.8	1.6	2.4	4.9	20.3	21.550, df=24 *P* = 0.606
	Writing and reading	13.8	4.9	13.8	11.4	11.4	55.3	
	Primary level (1-8 grade)	1.6	4.1	4.1	2.4	8.1	20.3	
	Above primary level	0.0	1.6	0.0	2.4	0.0	4.1	
	Total	17.1	20.3	19.5	18.7	24.4	100.0	
Livelihood source	Crop production	0.0	8.9	4.9	0.8	1.6	16.3	8.696, df =4 *P* = 0.069
	Mixed agriculture	17.1	9.8	14.6	17.9	22.8	82.1	
	crop production and trading	0.0	1.6	0.0	0.0	0.0	1.6	
	Trader	0.0	0.0	0.0	0.0	0.0	0.8	
	Total	17.1	20.3	19.5	18.7	24.4	100.0	

Source: own survey in 2020/21

5.3.2 Farmer assessment of soil quality

Farmers in the Choke have common criteria for identifying and evaluating their soil. The farmers' perception of soil fertility/ quality status is presented in Fig. 5.2. Of the overall respondents, more than half (73.6%) reported that their farmland is somehow fertile, 14% reported their farmland is fertile, and the remaining 12.4% reported low soil fertility (Fig 5.1).

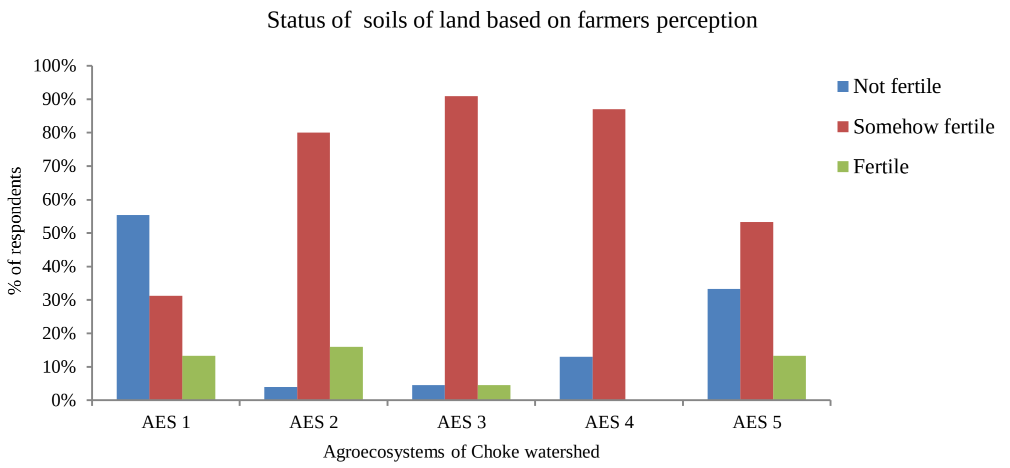


Figure 5.1 Status of soil or land based on farmers' perception

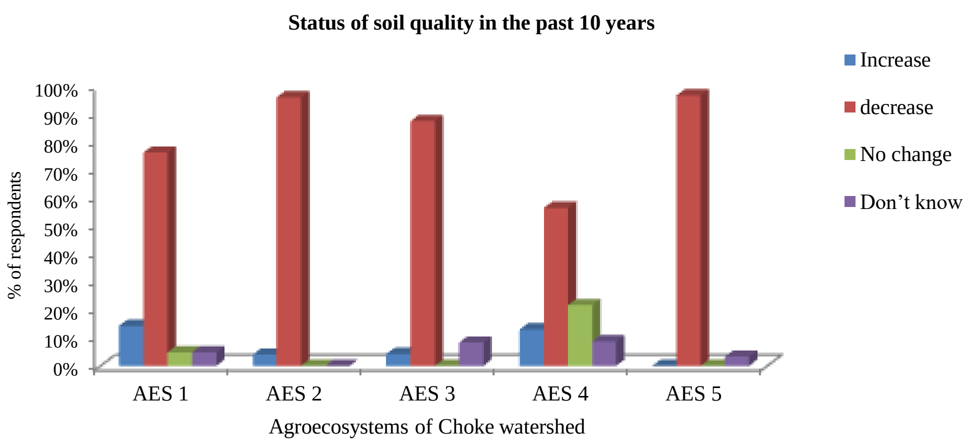


Figure 5.2 Farmers' perception of the status of soil quality in the past ten years

Besides, households in the Choke watershed asked about the trends of soil quality in the past ten years. As indicated in Fig 5.2, most farmers (87.3%) across the five AESs of the Choke watershed explain that soil quality has declined in the past ten years, and around 16.3% of respondents responded that there is no change, don't know, and increase. During the informal discussions, farmers and experts exhibited a solid knowledge of and comprehension of the cause of a decline in soil quality. They indicated that soil erosion followed by reduced soil fertility (soil nutrients) was a significant reason for the decline of soil quality and is considered a problem in almost all AESs of the watershed. These two major soil quality problems were highest, especially in the watershed's sloppy lands (AES 4) and hilly and mountainous highlands (AES 5) (Fig 5.3).

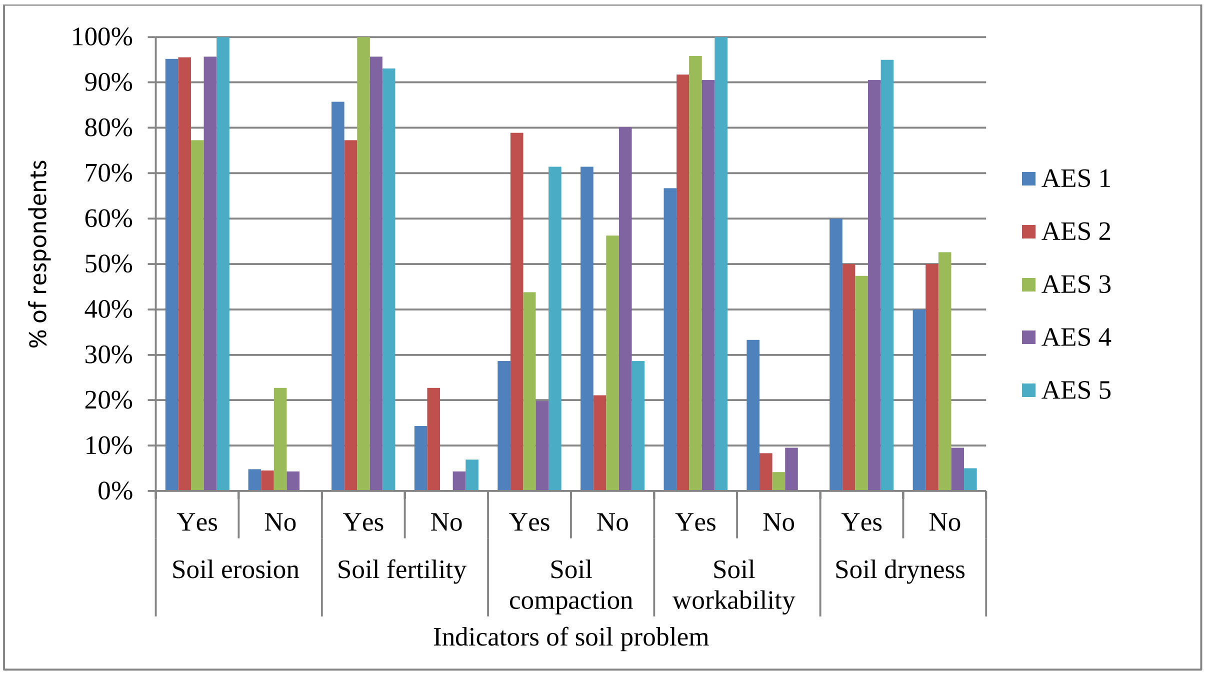


Figure 5.3 Major problems of soil quality

In addition, workability and soil dryness were also problems in the study AESs although there were farmers who voted 'No' (10.1% and 29.8%), they are not considered a problem of soil quality respectively among the overall farmer respondents. A result from farmers indicates that deforestation is a major accelerator for soil erosion, even if the seriousness of the problem was not equal among the AESs. Except for soil fertility problems, the other types of soil quality problems are significant among the agroecosystems.

5.3.3 Farmers' indicators of soil quality

It is clear from this study that farmers in the Choke have a well-defined and comprehensive set of indicators that they use to classify and assess the quality of their soils. Generally, these are characteristics they can see, feel, or smell in their fields and are based on their own experiences cultivating their farmlands.

Most Ethiopian farmers, including farmers from the Choke watershed, tend to have much more visual contact with their land (soil) to prepare for different crop production, and, logically, many look to crop performance and soil characteristics as an indicator of soil quality. Furthermore, the landscape position of their land had a significant impact on soil quality and was used as an indicator. Following the classification by Dawoe et al. (2012), farmer indicators were grouped into i) crop performance indicators (e.g., crop yield and leaf color), ii) soil characteristic indicators: (e.g., soil color, soil workability, and stoniness of the soil), iii) topographical characteristics (aspects relating to a field's location along the toposequnces) and iv) biological indicators (presence or absence of weeds).

5.3.4 Farmers' classification of soil quality

As indicated in Table 5.2, farmers' classification of soil quality was statistically significant among the five AESs of the Choke watershed. The farmers saw soil quality as dynamic since a particular unit of land can have high, medium, or low soil quality based on the type of management imposed or natural processes, including the erosion observed.

Soils that were perceived to be of high quality were described as supporting high crop yield with green leaf color, having black, dark brown, or dark gray surface soil color, easy to till, and requiring little power to pull implements with a few and no stones and pebbles which is an indicator of high water holding capacity. Furthermore, the low presence of weeds is one indicator of soil with high quality, according to farmers presented during the interview. Most farmers responding to high soil quality indicators were from AES 2 and AES 3 of the watershed (Table 5.2).

Similarly, soils that farmers classified to be of low quality were described as soils with the low-quality characteristics of all the indicators they used to classify. Soil's poor or low quality is characterized by the very low potential for crops that need more fertilizer inputs and is hard to plow with numerous stones and pebbles, which are difficult to till. Besides, light, light gray, or white color of soil, as they perceive from their experience throughout their lifetime, are also an indicator of low soil quality.

Table 5.2 Classification of soil quality based on farmers' indicators

Local knowledge and experience in Soil Quality classification.		Agroecosystems of Choke Mountain Watershed								
								Pearson Chi-Square		
Indicators	Classification of SQ	AES 1 N =21	AES 2 N=25	AES3 N=24	AES 4 N=23	AES 5 N=30	Total N=123	Value	df	P value
crop yield	High	0	15	12	1	2	30	61.701	8	0.000
	Medium	16	9	12	8	19	64			
	Low	5	1	0	14	9	29			
Leaf color	green	4	7	17	0	5	33	57.255	8	0.000
	light green	14	15	7	15	14	57			
	yellow	3	3	0	10	11	33			
Soil color	black or dark	5	20	8	0	3	42	42.265	8	0.000
	red or yellowish brown	10	5	14	17	12	56			
	white /light	6	0	2	6	15	19			
Soil workability	Tills easily and requires little power to pull implements	6	10	17	0	8	41	59.859	8	0.000
	Soil works reasonably well	10	13	7	5	7	42			
	soils hard to work	5	2	0	18	15	38			
Stoniness of soil	Few stones and pebbles are present	6	20	6	0	7	39	40.769	8	0.000
	stones present	6	4	9	8	14	41			
	numerous stones and pebbles	9	1	9	15	9	36			
Water holding capacity	High	0	13	6	1	2	19	59.041	8	0.000
	Medium	16	12	17	5	12	62			
	Low	5	0	1	17	16	37			
Presence of weeds	High	12	2	3	15	16	16	41.558	8	0.000
	Medium	9	7	4	5	11	51			
	Low	0	16	17	3	3	52			
Position on slope	Valley bottom	10	6	8	0	0	38	58.683	8	0.000
	middle slope	7	19	14	10	5	42			
	upper slopes/ summits	4	0	2	14	25	38			

Source: Field Survey, 2020/2021

5.3.5 Soil's physical and biochemical properties result

Munsell soil color chart report shows that various types of soil color were observed to sample soil for each agroecosystem. Light gray (10YR, 7/1) was observed at AES 1(lowland part of the watershed), including dusky red (2.5YR 3/3) (Table 5.3).

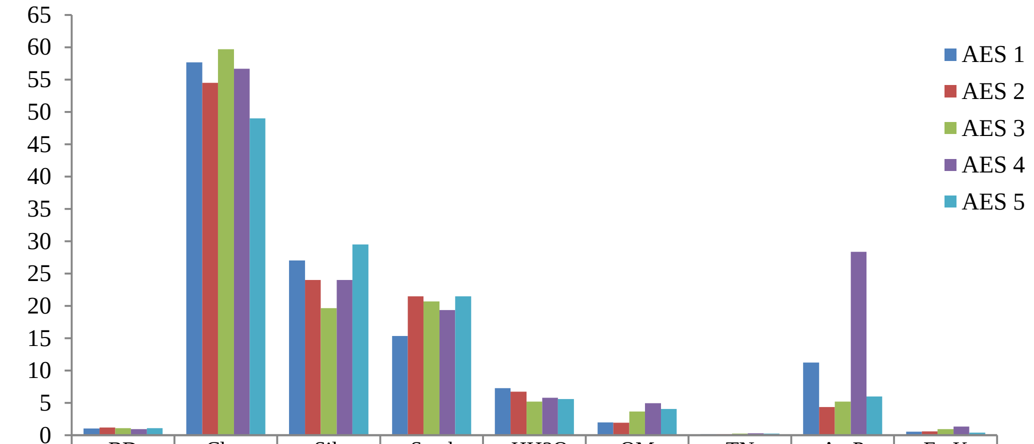
On the contrary, black (5YR, 2.5/1) is also found in the same AES. Similarly, some farmers from AES 1 perceived their farmlands' light/white color and the soil's low quality. Some others viewed red/yellowish soil colors (Table 5.3). A very pale brown (10YR 7/4) to black soil was recorded under AES 2 of the watershed. Likewise, the majority of farmers from AES 2 viewed their soil color as black/dark (an indicator of high soil quality) and some as brown (medium SQ) (Table 5.3).

Table 5.3 Results of Munsell color chart of the sample soil (20 cm depth)

AES	Field Code[10]	Hue, Chroma/Value	Color	Texture
AES 1	1TKUWhC	10YR, 7/1	Light Gray	C
	1TKUC	5YR, 2.5/1	Black	C
	2BKC	2.5YR 3/3	Dusky Red	C
AES 2	2SYC	5YR, 2.5/1	Black	C
	2SEC	10YR 7/4	Very Pale Brown	L
	2SHLC	2.5YR 3/3	Reddish Brown	C
	2BWC	5YR 2.5/1	Black	C
AES 3	3SYC	2.5YR 4/4	Dusky Red	C
	3BDC	10R 4/6	Red	C
	3SHEC	10R 4/6	Red	C
AES 4	4BAC	5YR 4/6	Yellowish Red	C
	4BAC	10R 3/6	Dark Red	C
	4SDC	7.5YR 6/4	Light Brown	CL
	4SEC	2.5YR 3/3	Dusky Red	C
	4TEC1	10R 3/6	Dark Red	C
	4TEC2	10R 3/3	Dusky Red	C
AES 5	5TDC	2.5YR 5/3	Weak Red	C
	5BGC	10R ¾	Dusky Red	C
	5FWC	10R 4/4	Weak Red	C
	5SDC	5YR 4/1	Dark Gray	CL

Note: AES, agroecosystem; AES 1, lowland and valley fragmented; AES 2, midland plains with black soil; AES 3, midland plains with brown soils; AES 4, midland sloping lands; AES 5, hilly and mountainous highlands; C, clay; CL, clay loam; L, loam

[10] In the field codes, the number one to five represents agroecosystems and letters represent the name of kebele followed by type of land (cultivated), where soil sample was collected.



	BD	Clay	Silt	Sand	pHH2O	OM	TN	Av.P	Ex.K
AES 1	1.03	57.67	27	15.33	7.26	1.98	0.13	11.23	0.52
AES 2	1.18	54.5	24	21.5	6.71	1.93	0.15	4.35	0.57
AES 3	1.06	59.67	19.67	20.67	5.18	3.64	0.22	5.21	0.95
AES 4	0.92	56.67	24	19.33	5.78	4.96	0.28	28.38	1.34
AES 5	1.08	49	29.5	21.5	5.61	4.05	0.23	6.01	0.38

Figure 5.4 Soil's physical and biochemical properties (20 cm depth) at the Choke watershed

Note: AES 1, lowland and valley fragmented; AES 2, midland plains with black soil; AES 3, midland plains with brown soils; AES 4, midland sloping lands; AES 5, hilly and mountainous highlands**;** BD, bulk density (g cm^{-3}); OM, organic matter (%); TN, total nitrogen (%); Av.P, available phosphorous (mg kg^{-1}); Ex.K, exchangeable potassium (cmol kg^{-1})

5.4 Discussion

According to Mairura et al. (2007), soil acidity, organic matter, nitrogen, phosphorus, and potassium are the most critical factors influencing and manifest crop growth characteristics related to the farmers' ability to recognize fields based on crop indicators. Results from the scientific analysis indicated a soil with a high pH level at the cultivated land was observed at AES 1. On the contrary, a very low or strongly acidic soil was found in AES 3 of the watershed, followed by AES 5 of the cultivated land (Fig 5.4). Soil organic matter was highest at the sloppy and mountainous highlands of the watershed and lowest at the lower part of the Abay valley (AES 1), followed by AES 2 of the watershed.

The soil analysis results indicate good agreement with farmers' assessment of soil quality in the Choke watershed, with some variation as results revealed. The study described the status of soil quality and indicators used to categorize soil quality as high, medium, and low as to local farmers' views. It was discovered that farmers' assessments of soil quality were consistent with those of Kuria et al. (2019) in Rwanda, Mairura (2007) in central Kenya, Dawoe et al. (2012) in Ghana, and Wawire et al. (2021) in upper Eastern Kenya suggesting that the findings of this study are pertinent and consistent with farmers' understanding of soil quality in a variety of agroecosystems.

Farmers from the five AESs of the study area explain their soil status depending on the characteristics of that particular AES in terms of crop performance, soil characteristics, topography, and the presence or absence of weeds. They perceived that soil quality status was decreased, especially in the sloppy and mountainous highland parts of the watershed, due to soil erosion and the decline of nutrients. Tesfahunegn et al. (2011) also found that soil erosion and fertility were a 'more problem' of soil quality in Northern Ethiopia's Mai-Negus catchment.

The scientific analysis of soil confirms these agroecosystems (AES 4 & 5) are highly affected by soil acidity due to the leaching of the base by the high amounts of rainfall. Farmers from the same AESs reported several critical signs of acid soils, including poor establishment, stunted development, pale green young seedlings, low stands, the poor tilling capacity of cereals, and poor crop production. All these signs are low soil quality. Decreasing acceptability of the soil for once common crops like barley *(Hordeum vulgare)* and faba beans *(Vicia fava),* as well as the different suitability of such soils for acid-tolerant crops like triticale, engido[11], and white lupin, are also the sign of soil acidity in the area (AES 4 & 5). Studies conducted by Abate et al. (2017) also reported soil acidity as a significant soil problem in the sloppy lands and highland parts of the watershed.

Soil color is a widely used indicator by farmers to classify soils in many parts of the globe (Corbeels, 2000; Dawoe et al., 2012; Wawire et al., 2021; Yageta et al., 2019). The color of the soil tails about, the organic content of the soil, and the dark color of the profile could be attributed to the presence of a higher amount of SOM, implying that darker soils were regarded to be more fertile (Wawire et al., 2021).

In the study field, most farmers also express that black soil represents high soil quality, and the Munsell soil color chart confirms such a point of view of farmers. Key informant interviews also replied the same result. However, the laboratory result of the soil shows somewhat different, and black soil is found in AES 2 of the watershed but with a low (1.93%)

[11] The term Engido comes from the Amharic word Engida, meaning stranger or newcomer.

(Fig 5.4) SOM concentration according to Tadesse et al. (1991) classification. The result disagrees with Wawire et al. (2021), who reported that darker soils have more SOM concentration than lighter soils and a higher soil water-holding capacity. This is because AES 2 is dominated by extensive areas of Vertisol, which are prone to severe waterlogging (soil compaction) during the rainy season. Farmers from this AES also perceived soil compaction problems more than other AESs (Fig 5.4). Albeit SOM was low in this AES, farmers were put under high soil quality classification using their indicators, including crop yield, which is high. Mesfin et al. (2022) confirmed the result and found a high soil quality index of AES 2 compared to other AESs. In line with the current study, Tesfahunegn et al. (2011) also found that high crop yield (more than 1.5 t ha^{-1} for teff) with a dark color of topsoil and high water holding capacity was an indicator of high soil quality as conducted in Northern part of Ethiopia.

However, Bicalho & Peixoto (2016) found that the colors of the mineral components tend to show through when organic matter reduces, thus indicating poor soil quality in that field. In contradiction, where farmers and even interviewed experts in the area perceived a low soil quality having red or yellowish soil (Table 2) recorded a high SOM (AES 4 & 5) (Fig 5.4). This variation may be attributed to the fact that since the area (AES 4 & 5) is degraded, farmers use various soil management practices, including liming and planting white lupine (*lupine albus*) for one to two years as a crop rotation method to replenish a degraded land (Fig 5.5). The lupin plant can fix nitrogen and mobilize phosphorus and other elements by exuding citrate into the soil, which is crucial for soil enrichment in barren areas (Rebolledo-Leiva et al., 2022).

Figure 5.5 Lupin plant that farmers used as a crop rotation method (AES 4)

Similarly, farmers witnessed the importance of such valuable legumes in their farmland and used them as a management practice, especially in AES 4 of the Choke watershed. That is why the major nutrient (available P) is highest in AES 4 of the Choke watershed. Local farmers' points of view about the leaf color of the crop express the scientific analysis of the level of phosphorous available in their soil. Thus it is better to use crop rotation methods like planting lupine in areas where the soil is degraded, which have economic and environmental purposes and sustain soil productivity.

5.5 Conclusion

This study aimed to evaluate farmers' perception and scientific analysis of soil quality indicators at the various agroecosystems of the Choke watershed. Farmers perceived that soil erosion and fertility/nutrient depletion are the significant problems that reduce soil quality in the study area, especially in sloppy and mountainous highlands of the watershed. Soil compaction or workability of soil is also a problem observed by farmers in AES 2 of the watershed. There is a good agreement between farmers' assessment of soil quality and scientific indicators such as pH and BD. The problem of soil acidity is recorded in the same area where farmers perceive soil erosion and the decline of nutrients due to erosion.

Farmers used crop yield and soil color as the most critical visual indicator to classify soil quality as high, medium, and low. As scientists obtained, the soil's black or dark color indicates high organic matter content. However, the current study disagrees with the result from scientists, where higher content of organic matter is found in areas where farmers perceive light/ yellowish soil color (AES 4 & 5) and less organic matter is recorded in the black color of soil (AES 2). The Munsell soil color chart also confirmed the soil color from the same site (agroecosystems) attributed to different climatic conditions, topographic features, soil type, parent material, and farming practices. On the other hand, a result from the two sides (farmers' view and scientific analysis) was similar in AES 1 of the watershed, where the soil color was white/light color, and less organic matter was observed.

The study results showed that farmers have well-developed indigenous knowledge about their soil based on own farming experiences and phenomena. Thus, to differentiate specific soil problems and to develop a site-specific (agroecosystem-based) sustainable soil management practice, it is better to support and motivate local farmers in participating them in soil management practices since they are very close to their fields in each activity of agriculture such as plowing, fertilizer application, growing season, harvesting, post-harvest, and marketing.

CHAPTER SIX

6. SYNTHESIS

6.1 Introduction

Soil is the foundation for nearly all land uses (Assefa, 2015). With water, soil constitutes the most important natural resource of our physical environment (Arshad & Martin, 2002; Lemenih, 2004). This vital resource is wise to promote sustainable development, feed the growing world population, and maintain environmental health (Arshad & Martin, 2002). How soils are managed has a significant impact on agricultural productivity and sustainability. Many agree that no agricultural system can be claimed to be sustainable without ensuring soil quality (fertility) sustainability. Since the maintenance or enhancement of soil quality is considered a key indicator of sustainable agricultural systems (Arshad & Martin, 2002), it is essential to assess soil quality.

Assessing soil quality is a sensitive and dynamic way to document soil condition, management response, and resistance to the stress imposed by natural forces (topography and climate) or human uses (land use and management). In a geographic location where various physiographic features like steep slopes, hilly lands, and mountainous surfaces are prevalent, topographic features, climatic elements, and vegetation cover significantly influence and characterize soil properties (Mohammed et al., 2018). Agroecosystems (AES), including the Choke watershed, a combination of agroecology, soil, terrain, and farming systems distribution, significantly affect soil quality indicators (Simane et al., 2013). Soil quality can be assessed by measuring soil attributes or properties that serve as soil quality indicators (physical, chemical, and biological) (Andrews et al., 2002). These indicators signal changes in soil quality at the different landscape and land use types (Seifu & Elias, 2018). The scientific analysis and farmers' understanding of soil quality also confirms the spatial variability of soil quality attributed to topography, land use, and management practice. Understanding how soil properties vary over agroecosystems (AES) in general and topo-sequence and land use type is essential for understanding soil potentials and improving site-specific agricultural management strategies for a sustainable ecosystem. This study focused on analyzing soil quality under the different topo-sequence and land use types and comparing it with farmers' view of their field's soil quality at the five Choke watershed agroecosystems. Hence, the major finding of each chapter of the study is summarized as follows.

6.2 Major Finding

The soil quality attributes in the Choke watershed vary significantly from the lowland and valley fragmented (AES 1) part of the Abay basin to the hilly and mountainous part of the watershed (AES 5). Silt content of the soil, exchangeable bases, cation exchange capacity, percent base saturation, pH, organic matter, total nitrogen, and available phosphorous varied significantly (P <.05, P <.01) across the five AESs of the watershed.

Most of the soil in the research area was composed of clay fractions, and all of the soils in the five AES of the Choke had clayey textures, except AES 3, which had clay loam as its textural class. The hilly and mountainous part of the Choke (AES 5) had the soil sample's highest mean silt and sand content. The middle and lower portions of the Abay basin have higher clay content deposited due to increasing soil erosion from the upper section of the watershed (**Chapter 2, Mesfin et al., 2022)**. Correspondingly, the soils at the upper landscape position of the watershed had a high mean value of silt, while the lower landscape position had the lowest, and the soils in the middle landscape had an intermediate silt content (Mesfin et al., 2022). The result could be because of the structural aggregation of silt and the accumulation of soil organic matter (SOM) in the Choke watershed's wet and high-altitude zones. AES 5 recorded the greater values of SOM and total nitrogen (TN) attributed to a cooler temperature (7.50C–100C) of the area, which slows the decomposition of SOM **(Chapter 2, Chapter 5, Mesfin et al., 2023; Mesfin et al., 2022)** and less addition of inorganic fertilizer to the soil **(Chapter 5)**.

Furthermore, climate (temperature and rainfall) and land use type within and across the watershed are vital in the SOM concentration. Grazing land in AES 5 of the watershed significantly affected SOM since animal grazing significantly impacts soil structure, function, and the ability to store nutrients. That is why a higher soil quality index was found in grazing land of the watershed. On the other hand, continuous and intensive land cultivation reduces the content of OM and records a low soil quality index across the watershed. **C**ompared with NFL, SQI values under PFL and CL were reduced by 10% and 19.7%, respectively, whereas SQI of GL was increased by 1.8%. SQI of CL was intermediate, whereas SQIs of GL, NFL, and PFL of the overall AES of the Choke watershed were high **(Mesfin et al., 2023).**

AES 2-intensively cultivated agroecosystems of the watershed, dominated by vertisol, are also affected by low SOM. The major problem of vertisol soil in AES 2 is waterlogging (compaction) during the high rainy season **(Chapter 2, 5)**. Soil compaction or soil workability is also a problem farmers observe in AES 2 of the watershed **(Chapter 5)—** however, the highest content of exchangeable bases, including Ca, Mg, and Ex. Na was recorded in AES 2 of the Choke and has a good soil quality index compared to other AESs (**Mesfin et al., 2023).**

Another essential soil nutrient that varied greatly (CV = 169%) among AESs of the Choke watershed was available phosphorous. It is one of the soil quality properties that were most variable in the study area. AES 1 and 4 have a medium available P, whereas AES 5 has a low available P, and AES 2 and AES 3 have a very low, which is deficient available P **(Chapter 2, Chapter 5, Mesfin et al., 2022)**. In addition, the topographic positions of each AESs also have a substantial effect on available P that might contribute to the strong interaction effects. The very low rate of available P was assigned to the middle landscape positions **(Mesfin et al., 2022).**

The alkaline soils (higher pH) in the lowland valley of the Abay basin (AES 1) may be responsible for the higher soil available P. The high calcium carbonate content of the soil within the area of AES 1 of the Choke watershed affected the pH of the soil. In addition, soil erosion affects the pH concentration in AES 1 of the Choke Mountain watershed. Since AES 1 is a lowland part of the watershed, the soil was leaching from the upper into the lower part containing nutrients (available P.), making the soil alkaline. The lowest mean value with the high soil pH acidity was reported in the upper position of AES 4 **(Mesfin et al., 2022)**. It might be attributed to leaching off base ions (Ca, Mg, and K) because of high erosion in AES 4. There is a high mean annual rainfall (1200–1400 mm) in AES 4 that contributes to the leaching of bases by erosion and constrains agricultural production. Farmers in such AES have abandoned their lands because of low crop productivity.

The cropping pattern in the area has also changed from initially grown crops (wheat and barley) to low-value crops (*Engido-Avena species*) because of low soil quality **(Chapter 2, Chapter 5, Mesfin et al., 2023, 2022).** Farmers from the same AES (AES 4) also reported several critical signs of acid soils, including poor establishment, stunted development, pale green young seedlings, low stands, and poor tilling capacity of cereals, and therefore poor crop production and perceived the area with low soil quality **(Chapter 5).**

Crop production and soil color were farmers' most critical visual indicators for categorizing soil quality as high, medium, or low. As discovered by scientists, a soil's black or dark color denotes a significant level of organic matter. The current study, however, deviates from the experts' findings in that it records higher levels of organic matter in places where farmers perceive light/yellowish soil color (AES 4 and 5) and lower levels of organic matter in areas where farmers perceive black soil color (AES 2) **(Chapter 5).**

6.3 Contribution of the Study

This study is important because it provides insights into the variability of soil quality across different land use types and topographic positions in agroecosystems. By collecting data from both soil and socioeconomic surveys in five agroecosystems, the researchers gained a comprehensive understanding of various soil quality indicators and their implications for agriculture. They identified significant soil quality indicators and how they varied depending on topography and land use type. This information can help farmers and policymakers make informed decisions about soil and crop management practices to improve soil quality and sustain agricultural productivity.

The study's findings have potential implications for agriculture and sustainable development. Policymakers and development actors including agricultural extension providers and advisors can use this information to make better decisions about soil, water, and crop management practices, leading to more sustainable agriculture and environmental sustainability. Additionally, comparing scientific soil quality assessments with farmers' perceptions of soil quality highlights the need for increased farmer participation in soil management decisions.

In the long term, this study aligns with the United Nations' Sustainable Development Goals (SDGs), as it promotes sustainable land and soil management practices. The study also benefits water resources in the upper Blue Nile Basin by improving soil quality, which helps the area retain more water, providing freshwater and water for agriculture to millions of people in Ethiopia, Sudan, and Egypt.

Furthermore, the study used statistical tools like principal component analysis (PCA), ANOVA (Analysis of Variance), MANOVA (Multivariate Analysis of Variance), and soil quality index (SQI) to analyze the soil quality data, providing a scientific basis for the conclusions. Using ANOVA and MANOVA in soil science research has contributed significantly to understanding the effects of different factors (such as topography, land use, and soil type) on soil quality attributes and their interactions. These statistical tools allow researchers to compare means among different groups. The Soil Quality Index (SQI) is a composite index that combines multiple soil quality indicators into a single score, allowing researchers and farmers to assess soil quality more easily and comprehensively. Using the SQI has contributed to developing more sustainable soil management practices, allowing for a more holistic assessment of soil health and productivity.

Overall, using these statistical tools in soil science research has helped identify the factors that affect soil quality and develop more effective management practices to maintain or improve soil health, which in turn contributes to sustainable food production, environmental protection, and human well-being.

6.4 Conclusion

This study found that farming systems with various soil management practices, land use land cover, agro-climatic variability of the area, and soil type of AES with varying landscapes were the critical factors responsible for the variability of soil quality indicators in the Ethiopian highlands in general and in the Choke watershed in particular. The result revealed that the measured soil quality attributes varied significantly among the five AES of the Choke.

Soil quality indicators varied along with topo-units and across the five AES of the Choke Mountain watershed. All AES was under the range of higher CEC. Clayey textural class dominates agroecosystems of the Choke watershed, indicating similar parent material, except AES 3, which had clay loam as its textural class. The study shows that the silt content of the soil increases with the increasing slope of the watersheds. Increased soil erosion from the upper part of the watershed deposited in the middle and lower portions of the Abay basin, which have higher soil clay contents, could be the cause.

Both AES and topo-unit uniquely affected the OM content of the soil, being higher in AES 5 and lower in AES 1. The variation might be attributed to climate, farming system, land use, land cover, and management practices, especially the tillage intensity across the five AES. Increasing tillage for cultivated land induces quick decomposition of SOM, reducing SQI under Choke watershed cultivated land. Furthermore, pH increases as the landscape's slope decrease. The lowest pH in the soils of the upper landscape position because of the loss of exchangeable bases caused by runoff and erosion was a reason for the lower value of SQI of PFL in AES 4 of the watershed, whereas SQI of GL was higher in AES 2, followed by AES 3. AES 2 of the watershed recorded the highest total SQI value and the lowest in AES 5 of the Choke watershed because of the steepness of the area and vulnerability to soil erosion. Among AES of Choke, However, in AES 4, higher SQI was found in NFL, and lower SQI was recorded under the PFL of the area.

Farmers also perceived that soil erosion and fertility/nutrient depletion are the significant problems that reduce the quality of soil in the study area, especially in sloppy and mountainous highlands of the watershed. They classified their land's soil quality based on crop performance, soil-related characteristics, and the topography of their field with other biological indicators. The study results show that farmers have well-developed local knowledge about their soil based on their farming experiences and phenomena.

6.5 Recommendation

Based on the study's findings, the following recommendation was suggested for sustainable soil quality management and agriculture.

- Unless acidity is reduced, cultivating their land won't be easy. The present study revealed that soil acidity is the major problem of the area, especially AES 3 & 4 of the Choke watershed. Thus the local government should help farmers to reduce soil acidity through the addition of lime to the cultivated land, which supplies essential plant nutrients such as Ca and Mg, preventing Mn and Al from being toxic to crop growth.
- There is also a need to improve soil fertility status in those AES affected by leaching and soil nutrient depletion. Therefore farmers would be advised to use efficient and practical soil management techniques. In particular, lime and organic fertilizer (compost and manure) application are essential.
- Reduced tillage intensity and integrated, multifunctional agricultural rotations that contain forage legumes will increase SOM and improve the soil quality of cultivated land and the environment for soils afflicted by soil compaction and low OM content. The agricultural development agents should create awareness among local farmers through training or practicing in their field.
- Site-specific land use and management practices across the various AESs should be recommended to land managers and farmers to sustain the AESs of the Choke watershed.

- The government should support and motivate local farmers to participate in soil and land management practice since they are very close to their fields in each agricultural activity, such as plowing, fertilizer application, growing season, harvesting, post-harvest, and marketing.

6.6 Future Research

Based on the limitations and findings of this study, the following key research areas are proposed for the future:

- ✓ The number of soil samples used to analyze soil quality across the agroecosystems of the Choke watershed is limited. Since soil is site-specific, it is essential to consider a large number of soil sample sizes from each landscape and land use type among the study agroecosystems, which helps to generate detailed and more site-specific data and information on the soil quality of the study area.
- ✓ Although the soil's organic matter is often considered the critical quality factor of the soil and is highly correlated to numerous factors influencing productivity and environmental sustainability, it is better to use microbial organisms, mineralizable nitrogen, and other soil organisms. Because microorganisms in the soil contribute to the improvement and maintenance of soil quality and control the decomposition of plant and animal materials, the rate of biogeochemical cycling aid in forming soil structure and the fate of organic chemicals in the soil. Thus, this research suggests future researchers use microorganisms as a biological indicator of soil quality in each agroecosystem of the watershed.
- ✓ Based on which soil quality indicators are in a state of degradation, appropriate changes in management, such as the application of fertilizers, additional irrigation, or reduction in pesticides, may be needed to correct various soil parameters and to reach ideal or acceptable conditions. It is better to research the selection of appropriate remedial management for degraded indicators for specific landscape and land use types in each agroecosystem.
- ✓ The details of plantation forest (eucalyptus forest) need further research as it degrades, improves, or maintains soil quality at an agroecosystems level of the watershed.

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Appendix 1 Household survey

Addis Ababa University

College of Development studies

Department of Environment and Development

Dear respondents: the primary purpose of this study is to understand farmers' perception of the soil status of cultivated land in the Choke agroecosystems to compare with the scientific analysis of soil quality. Your genuine responses to these questions help the study's better outcome. Therefore, you are kindly requested to give your genuine response.

General information: Demographic and Socioeconomic Characteristics

Name of data collector________________________ Questionnaire code: _______________

AES__________Kebele_______________Village____________________Date___________

1. Sex: 1. Male 2. Female.
2. Age 1. 20-29 2. 30-39 3. 40-49 4. $\geq$50
3. Marital status: 1. Single 2. Married 3. Divorced 4. Widowed
4. Educational status: 1. Illiterate 3. Primary level (1-8 grade
   2. Writing and reading 4. Above primary level
5. Livelihood source 1. Crop production 3. Mixed agriculture
   2. Livestock 4. Government civil servant
   5. other, please specify___________________________________

Part I: Land use

1. Do you have your own land 1. Yes 2. No
2. What is the status of your cultivated land fertility?
   1. Not fertile 2. Somehow fertile 3. Fertile 4. Highly fertile
   please specify____
3. What type of soil is your cultivated land? 1. Black 2. Brown 3. Red 4. Other_____
4. How is the slope of your cultivated land?
   1. Plain 2. Hilly 3. Highly sloppy 4. Mountainous

5. Other,___________________

Part II:- Local knowledge and experience on soil quality status.

5. Is there any problem with your soil quality or land? 1. Yes 2. No
6. How do you see soil quality status in the past ten years?
   1. Increase 2. Decrease 3. No change 4. Don't know
7. What are the indicators that you are used to judging the status of soil quality for your cultivated land? Multiple responses are possible.

   1. Crop performance 3. Topographical factors

   2. Soil characteristics 4. Biological indicators 5. Specify others___________

8. How do you explain the quality of the soils of your farmland based on the following characteristics? Fill in the table below based on the clue.

Crop yield: consistently high yields, medium, low yields

Leaf color of growing crop: large green leaves… small, yellowish, and narrow leaves

Color of soil: black or dark… red or yellowish brown…….white /light

Presence of indicator weeds: high…medium….low

Stoniness of soil: Few stones and pebbles present…stones present…many stones and pebbles

Soil workability: Tills easily and requires little power to pull implements…. Soil works reasonably well…. soils hard to work

Water holding capacity: high… medium…. low

Position on a slope: Valley bottom...middle slope… upper slopes/ summits

Indicators	High soil quality	Medium soil quality	poor soil quality
1. Crop performance			
Crop yield			
Leaf color			
2. Soil characteristics			
Soil color			
Soil workability			
Stoniness of soil			
Water holding capacity			
3. Biological characteristics			
Presence of indicator weeds			
4. Topographical factors			
Position on slope			

9. How do you see the rate of soil quality status problems on your farm?

   1. Very High 2. High 3. Medium 4. Low 5. Very low

10. What indicators do you use to know the problem of soil quality? Rank them based on the level of the problem.

Soil quality indicators	1. Yes,	2. No.	Problem (1st, 2nd, 3rd,4th, 5th)
Soil erosion			
Soil fertility			
Soil compaction			
Soil workability			
Soil dryness			

11. What soil quality indicators do you use to categorize soil quality status as high, medium, or low

SQ indicators	1. Yes	2. No
Soil compaction		
Soil erosion		
Easiness to tillage and workability		
Texture		
Soil color		
Topsoil thickness		
Water holding capacity in the dry season		
Soil fertility		
Fertilizer response of soil		
Crop yield		
Crop performance/vigor		
Weed infestation		

Appendix 2 Guidelines for key informant interview

1. How do you perceive soil quality status and trends in the last ten years?
2. What are the major soil quality problems observed in the study agroecosystem of the Choke watershed?
3. What indicators do you and local farmers use to identify the land's soil quality?
4. What do you understand from the color of the soil?
5. How do you see the topography of your land and its effect on soil?

Appendix 3 Images

A. Soil sampling from land uses

B. Topographic dissection and erosion