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DOCTORAL (PHD) DISSERTATION

SOIL ORGANIC CARBON STOCK DYNAMICS AS INFLUENCED BY LAND USE, ELEVATION, AND MANAGEMENT PRACTICES: A CASE STUDY OF THE EASTERN SLOPES OF MOUNT KENYA

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BY

BRIAN ROTICH KANYONGI

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Title: Soil organic carbon stock dynamics as influenced by land use, elevation, and management practices: A case study of the eastern slopes of Mount Kenya.

Discipline: Environmental Sciences

Name of Doctoral School: Environmental Sciences

Head: Csákiné Dr. Michéli Erika

Professor, DSc.

MATE, Doctoral School of Environmental Sciences

Department of Soil Science

Supervisors: Dr Csorba Ádám

Assistant professor, PhD

MATE, Doctoral School of Environmental Sciences

Department of Soil Science

Dr Caleb Melenya

Assistant professor, PhD

MATE, Doctoral School of Environmental Sciences

Department of Soil Science

....

Approval of the Head of Doctoral School Approval of the Supervisor(s)

DECLARATION

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……………….. ……………… Date: ………………………………...

DECLARATION BY SUPERVISORS

This dissertation has been submitted with our approval as supervisors.

………………………………. Date: ………………………………….

Dr Ádám Csorba
Assistant professor, PhD
MATE, Doctoral School of Environmental Sciences
Department of Soil Science

……………………………… Date: …………………………………….

Dr Caleb Melenya
Assistant professor, PhD
MATE, Doctoral School of Environmental Sciences
Department of Soil Science

DEDICATION

This work is dedicated to my mother ***Tabitha Nasambu James***, who has been a great inspiration and influence in my academic journey.

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LIST OF ABBREVIATIONS AND ACRONYMS

AEZs: Agroecological zones

ANOVA: Analysis of Variance

BD: Bulk density

CBO: Community Based Organization

COP: Conference of the Parties

C: N: Carbon to nitrogen ratio

FAO: Food and Agriculture Organization of the United Nations

g cm^{-3}: Gram per centimetre cube

g C kg^{-1}: Grams of carbon per kilogram of soil

GHG: Greenhouse gases

GIS: Geographic Information System

GLM: General Linear Model

GPS: Global Positioning System

GRV: Great Rift Valley

HH: Household

HSD Test: Honestly Significant Difference Test

HWSD: Harmonized World Soil Database

IBA: Important Bird Area

ITPS: Intergovernmental Technical Panel on Soils

IUSS: International Union of Soil Sciences

KFS: Kenya Forest Service

KII: Key Informant Interviews

LDM: Laser Diffraction Method

LULC: Land use/Land cover

Mg ha^{-1}: megagrams of carbon per hectare

MoALF: Ministry of Agriculture, Livestock and Fisheries

NACOSTI: National Commission for Science Technology and Innovation

ODK: Open Data Kit

Pg: Petagram

RSMPs: Recommended Management Practices

RSG: Reference Soil Groups

SD: Standard Deviation

SDGs: Sustainable Development Goals

SFM: Sustainable Forest Management

SOC: Soil Organic Carbon concentration

SOCS: Soil Organic Carbon Stock

SOM: Soil Organic Matter

SSA: Sub-Saharan Africa

SWCPs: Soil and Water Conservation Practices

Tg: Teragrams

t/ha: Tonnes per hectare

TN: Total Nitrogen

TNC: Tharaka Nithi County

UNFCCC: United Nations Framework Convention on Climate Change

VIF: Variance Inflation Factor

WRB: World Reference Base

1. INTRODUCTION

This is the first chapter which introduces the study. The chapter is organized into the following sub-sections: background information, which gives a general overview of Soil Organic Carbon, general statistics, its significance, dynamics, and distribution determinants; the problem statement highlights the existing research gaps to be filled by this study; the broad and specific research objectives; research questions; the justification for the study in the local, regional, and global context, limitations of the study and finally the working definition of common terms used in this study.

1.1 Background information

Soils are integral to the functioning of all terrestrial ecosystems and food and fibre production (Paustian et al., 2016). Soil organic carbon (SOC) is critical for food production, climate change mitigation, and achieving Sustainable Development Goals (FAO & ITPS, 2020; Yang et al., 2023). There are five main global carbon pools that are interconnected; the oceanic pool (38000 petagrams [pg]), geologic pool (5000 pg), soil pool (2500 pg), atmospheric pool (760 pg), and biotic pool 560 pg (Lal, 2004b). After the oceanic and geologic carbon pools, the soil carbon pool is the third largest globally. The total soil carbon pool is estimated to be four times the biotic pool and about three times the atmospheric pool (Bradford et al., 2019; Lal, 2004b; Larionova et al., 2015). SOC significantly contributes to the global carbon budget due to its role in the carbon cycle. It serves as a source or sink of atmospheric carbon, thereby affecting climate change (Martin et al., 2011; Xin et al., 2016). Because it influences the soil's physicochemical properties, SOC is also an effective indicator for assessing soil fertility, soil health, and soil quality. SOC influences soil fertility bases such as soil structure, cation exchange capacity (CEC), and water-holding capacity (FAO & ITPS, 2020; Sullivan et al., 2005; Wang et al., 2015).

For accurate estimation of Soil Organic Carbon Stocks (SOCS), it is essential to understand the spatial distribution and controlling factors of SOC at various scales. This knowledge is necessary for assessing the effect of soil management practices on soil quality and developing practices that promote sustainable agriculture (Fu et al., 2023; Yu et al., 2020). Understanding the spatial dynamics of SOCS and the factors that influence the global carbon cycle is also critical for improving our ability to predict and mitigate the effects of climate change (Fu et al., 2023; Laganière et al., 2010). Most of the world's SOC is stored at northern latitudes, particularly in the northern permafrost regions (Scharlemann et al., 2014). The global SOC is estimated at 684–724 Pg of Carbon (C) in the top 30 cm, 1462–1548 Pg of C in the upper 100 cm, and 2376–2456 Pg of C in the upper 200 cm and over 2300 Pg of C in the top 300 cm (Batjes, 1996; Jobbágy & Jackson, 2000).

The SOCS is governed by factors that influence the build-up and the removal of carbon (Ahmad Dar & Somaiah, 2015). The interactions of ecosystem processes like photosynthesis, respiration, and decomposition determine the SOC levels. SOC storage in the soil is controlled by the balance of C inputs from plant production and outputs through decomposition (Ontl & Schulte, 2012). The fluctuations of SOCS vary in response to a number of environmental and anthropogenic drivers (Stockmann et al., 2013). Environmental factors affecting the quality, quantity, and distribution of SOCS include topography, vegetation, climate, parent material, soil texture, and land use (Dobos et al., 2005; Fu et al., 2004; Liu et al., 2011; Wang et al., 2018; Wang et al., 2014; Xin et al., 2016). The land use type influences the SOCS by affecting the amount of organic carbon inputs, the rate of litter decomposition and stabilization (Ali et al., 2017; Dorji et al., 2014). Similarly, the altitudinal gradient affects the SOC by controlling precipitation, temperature regimes, relative humidity, solar radiation, and geologic deposition processes (Kong et al., 2022; Tsui et al., 2004, 2013). In agricultural lands, crop and soil management practices by humans, such as crop species and rotation, tillage methods, fertilizer volume, manure application, pesticide usage, irrigation, and drainage, as well as soil and water conservation, all have a significant impact on the SOC content (Francaviglia et al., 2023; Heenan et al., 2004; Lal, 2002; Peng et al., 2013). Therefore, depending on the carbon fluxes, soils may act as either a sink or a source of atmospheric carbon dioxide (CO_2) (Schrumpf et al., 2011).

The global significance of SOC in agriculture has been recognised in recent times, as demonstrated by its inclusion on the agenda of the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris (COP21) for the first time since its inception about two decades ago (Lal, 2016). The "4 per mille or 4 per 1000" proposal was launched in December 2015 and supported by almost 150 signatories. It aspires to increase and enhance global Soil Organic Matter (SOM) stocks to a 40 cm (16 inches) depth by 0.4% annually as compensation for the global emissions of greenhouse gases (GHGs) from human sources (Lal, 2016; Minasny et al., 2017). The proposal aims at promoting SOC sequestration through the adoption of Recommended Soil Management Practices (RSMPs) of C farming via conservation agriculture, agroforestry, cover crops, mulching, improved grazing, use of biochar, and restoration of degraded soils through soil landscape restoration programs (Lal, 2016).

1.2 Problem statement

The SOC pool plays a significant role in the global C cycle as minor changes in the soil C pool can translate into large changes in the atmospheric pool (1 Gt of the soil C pool = 0.47 ppm of CO_2 in the atmosphere) (Lal, 2016). SOCS are dynamic and are significantly influenced by various environmental and anthropogenic factors, including land use, elevation, and management practices. Better estimates of SOCS and SOC dynamics are required for an improved understanding of the carbon balance and its potential in mitigating climate change (Scharlemann et al., 2014). Much of the SOC losses in Kenya have been attributed to the rapid expansion of agricultural lands and the conversion of natural habitats like forestland and grassland into croplands (Vågen & Winowiecki, 2013). Consequently, many croplands in Kenya have been over-exploited, in addition to the application of unsustainable agricultural practices by farmers resulting in nutrient loss and organic matter depletion (Batjes, 2004). The Mount Kenya region in central Kenya is one of Eastern Africa's most significant agricultural production and conservation areas due to its unique climate, vegetation, soils, and elevation profile. While existing studies in Kenya have examined the individual effects of elevation, land use and management practices on SOCS (Muhati et al., 2018; Njeru et al., 2017; Segnini et al., 2019; Tarus & Nadir, 2020; Wawire et al., 2021; Were et al., 2016; Were et al., 2015), there is a dearth of comprehensive research hitherto that considers their combined influence in specific landscapes, particularly in mountain ecosystems like Mount Kenya. This study, therefore, aims to bridge the gap by investigating the variability of SOCS on the eastern slopes of Mount Kenya along an elevation gradient and under different land use types and management practices.

1.3 Research objectives

1.3.1 Broad objective

The main objective of this study was to investigate the influence of elevation, land use, and management practices on SOCS and assess the determinants and challenges of RSMPs adoption on the eastern slopes of Mount Kenya.

1.3.2 Specific Objectives

To achieve the broad objective, the following specific objectives were defined.

1. To compare SOC concentrations and stocks under forestland and farmland and different soil depths on the eastern slopes of Mount Kenya.

2. To assess the variation of SOCS along the elevation gradient on the eastern slopes of Mount Kenya.
3. To characterize RSMPs in the study area, determine factors influencing their adoption among farmers, and assess the challenges hindering their uptake.
4. To evaluate the influence of RSMPs on SOCS on the eastern slopes of Mount Kenya
5. To assess farmers' SOC and SOM knowledge and perceived benefits on the eastern slopes of Mount Kenya.

1.4 Research questions

1. To compare SOC concentrations and stocks under forestland and farmland and different soil depths on the eastern slopes of Mount Kenya:
   - 1.1. How do the physicochemical properties of forestland and farmland soils in the study area compare?
   - 1.2. What are the average SOC concentrations and stocks in the forestland and farmland on the eastern slopes of Mount Kenya?
   - 1.3. How do SOC concentrations and stocks vary between the soil depths on the eastern slopes of Mount Kenya?
2. To assess the variation of SOCS along an elevation gradient on the eastern slopes of Mount Kenya:
   - 2.1. What is the pattern of variation in SOCS along the elevation gradient on the eastern slopes of Mount Kenya?
   - 2.2. How do SOCS change with increasing elevation in the study area?
3. To characterize RSMPs in the study area, determine factors influencing their adoption among farmers, and assess the challenges hindering their uptake:
   - 3.1. What is the demographic, socio-economic and farm characteristics of the households in the study area?
   - 3.2. What are the RSMPs adopted by farmers on the eastern slopes of Mount Kenya to enhance SOCS and reduce SOM loss?
   - 3.3. What factors influence farmers' decisions to adopt these RSMPs?

3.4. What are the key challenges hindering the adoption of RSMPs in the study area?

4. To evaluate the influence of RSMPs on SOCS on the eastern slopes of Mount Kenya
    4.1. Which RSMPs have a significant influence on SOCS in the study area?
5. To assess farmers' SOC and SOM knowledge and perceived benefits of SOM on the eastern slopes of Mount Kenya.
    5.1. What is the level of awareness among farmers about SOC and SOM?
    5.2. What are the local indicators of soils with high SOM content used by farmers in the study area?
    5.3. What are the perceived benefits of maintaining high SOM content in the soil by farmers on the eastern slopes of Mount Kenya?

1.5 Justification

The SOC plays a critical role in the global carbon cycle, and its management has the potential to offset carbon emissions (Batjes, 1996). Due to its fundamental role in the global carbon cycle and its potential to either reduce or increase atmospheric concentrations of GHGs, SOC pools have received a lot of attention in recent times (Lal, 2004b; Raich & Potter, 1995). Land cover, soil management practices, and altitudinal delineations are crucial determinants of spatial soil nutrient patterns in East African mountain ecosystems (Namirembe et al., 2020; Njeru et al., 2017). The eastern slopes of Mount Kenya offer a unique landscape with varying elevation gradients and land use practices. This variation can provide insights into how these factors interact and influence SOC dynamics. Understanding the factors that influence SOC dynamics is crucial for developing effective climate change mitigation strategies and also provides a baseline for assessing future changes (Wang et al., 2023).

Elevation differences impact temperature and precipitation patterns, which in turn influence soil microbial activity and SOM decomposition rates (Jasso-Flores et al., 2020). Investigating the effects of elevation on SOCS is crucial for understanding ecosystem responses to climate change. Changes in temperature and precipitation patterns due to elevation differences may cause shifts in vegetation composition, altering SOC inputs to the soil (Tsozué et al., 2019). Different land use types, such as agriculture, deforestation, and reforestation, can significantly alter SOCS (Guo & Gifford, 2002). Soil management practices in agricultural lands also have varying impacts on the SOC content (Francaviglia et al., 2023). Soil management practices, including agroforestry, manure application, mulching and conservation tillage, can influence

SOC accumulation and losses; therefore, identifying effective management strategies can contribute to enhancing SOCS (Lorenz & Lal, 2014).

This study addresses a significant knowledge gap by investigating the interactions between land use, elevation, soil depth and management practices in influencing SOC dynamics. Insights from this study have both local and global implications. Locally, it can aid local administration and communities in making informed decisions about land use and soil management practices. It also conforms to the country's national short term and long-term development blueprints including the bottom up economic model (agriculture, environment and climate change), big four agenda (food security), and Kenya Vision 2030 (Government of Kenya, 2007). Globally, it contributes to the scientific understanding of SOC dynamics, specifically in a tropical montane landscape (Lal, 2004a). The research also aligns with some of the United Nations' Sustainable Development Goals (SDGs), including SDG 1 (no poverty), SDG 6 (clean water and sanitation), SDG 13 (climate action) and SDG 15 (life on land), by contributing to climate change mitigation efforts and sustainable land management practices (United Nations, 2015).

The findings have the potential to inform land management strategies, contribute to climate change mitigation efforts, and advance scientific understanding in the field of ecosystem ecology. The study's integration of field surveys, social surveys, modern laboratory analyses, and Geographic Information System (GIS) techniques further contributes to the advancement of modern methodologies for studying complex ecological systems such as Mt Kenya.

1.6 Limitations of the study

Although the study addresses existing research gaps cited in earlier studies, it still has some limitations. Sampling in the forest was particularly challenging owing to the rugged terrain, accessibility due to thick forest stands, and safety issues, as the Mt Kenya forest is home to dangerous wild animals like buffaloes, leopards, and elephants. This challenge was, however, overcome by tagging along two forest ranges for security provision and guidance in navigating through the thick forest. The household (HH) survey data was based on respondents' memory and willingness to give genuine information. Key Informant Interviews (KII) and field observations were also used to strengthen and bridge the gap that might have emanated from the HH surveys.

1.7 Definition of operational terms

Forestland: A land area over 0.5 ha dominated by trees greater than 2 m in height, with a crown cover greater than 15% (FAO, 2015).

Farmland: Tilled land and land under cultivation of annual, biennial, and perennial crops.

Elevation gradient: Elevational ranges exhibiting variations in abiotic conditions over short distances.

Land cover: Observed physical cover on the earth's surface, including vegetation (natural or planted) and human constructions (Nedd et al., 2021).

Land use: The arrangements, activities, and inputs people undertake in a certain land cover type to produce, change, or maintain it (Nedd et al., 2021)..

Household (HH): A group of related or unrelated people living together, sharing resources, expenditures, and activities.

Soil Organic Matter (SOM): Fraction of the soil originating from plant or animal tissues at various stages of decomposition (FAO, 2017).

Recommended Soil Management Practices (RSMPs): Soil management practices that aim to enhance Soil Organic Carbon and reduce SOM losses via erosion.

Climate change: Change of climate which is directly or indirectly attributed to human activity that alters the composition of the global atmosphere. These changes are in addition to the natural climate variability observed over comparable time periods (UNFCCC, 1992).

2. LITERATURE REVIEW

2.1 Introduction

This section presents a detailed review of existing literature relevant to the study objectives, with the aim of identifying the knowledge gaps and providing justification for this study. The chapter is organized under several sections as follows.

The first part provides an overview of SOC concepts and the importance of SOC in terrestrial ecosystems. The components of SOC are defined, the role of SOC in soil health and ecosystem services is highlighted, concept soil carbon sequestration, common SOC determination methods and calculation of SOCS are detailed. The second part explores the various factors influencing SOCS and its dynamics. Further literature on SOC distribution and stocks worldwide, in Africa and in Kenya is also provided. The third part highlights SOC and Stocks under different land use types. Comparison of SOC concentrations and stocks in different land use types and implications for ecosystem carbon storage is also covered. Land Use Land Cover (LULC) types and changes in Kenya are also detailed in this chapter. Here, the different classes and coverage of land use types and their changes over time in Kenya are highlighted. Variations of SOCS along an elevation gradient, factors contributing to elevation-based SOC variations, and implications of slopes and elevations for regional carbon cycling are also reviewed in this section. Additionally, the elevation gradient of Kenya is described. The fourth part reviews RSMPs for enhancing SOCS and reducing SOM losses. The challenges and limitations in implementing these practices are also reviewed.

2.2 Soil Organic Carbon concepts and importance

2.2.1 Definition and components of SOC

SOC is defined as C in the soil from an organic origin (Wander, 2004). There are five main global C pools, which are interconnected, comprising the oceanic pool (38000 pg), geologic (5000 pg), soil (2500 pg), atmospheric (760 pg), and biotic (560 pg) (Lal, 2004b). Soil contains approximately 2,344 gigatons (Gt) (1 gigaton = 1 petagram = billion tonnes) of organic carbon globally, making it the largest terrestrial pool of organic carbon (Stockmann et al., 2013). The soil (pedologic) C pool comprises two components; SOC and the soil inorganic carbon (SIC) pool. The SIC pool mainly consists of carbonates and bicarbonates and forms significant components of the soils in the dry regions, while SOC is the main element of SOM that is readily measured quantitatively (Lorenz & Lal, 2018). SOM is the major reservoir of terrestrial SOC and represents a significant C pool (Schmidt et al., 2011). The SOM comprises fresh plant and animal residues, which can decompose to release nutrient elements. SOM contains about

55–60 % of SOC by mass. In many soils, this C makes up most or all the C stock (SOC) except in cases where inorganic forms of soil C occur (FAO & ITPS, 2015). SOM can further be categorised into the active and passive pools in accordance with their turnover rates (von Lützow et al., 2007; Wiesmeier et al., 2014). The active pool has a short turnover time of between 1–10 years, while the passive pool has a considerably longer turnover time of more than 100 years (Christensen, 2001; Six et al., 2002).

Similarly, SOC is divided into three different pools as a function of its physical and chemical stability for modelling purposes. These pools include the labile/fast/active pool, the intermediate pool, and the refractory/slow/stable pool (FAO & ITPS, 2015). The active pool comprises easily degradable plant material, labile metabolites, and microbial biomass, which decompose within a few months or years. The intermediate pool represents microbially processed organic matter that is partially stabilized on mineral surfaces and/or protected within aggregates, with turnover times in the range of decades (10–100 years). The stable pool includes highly stabilized organic matter mineral complexes and pyrogenic C, with very slow turnover rates ranging from 100 to over 1000 years (FAO, 2017; FAO & ITPS, 2015).

2.2.2 Role of SOC in soil health and ecosystem services

SOCS refers to the amount of organic carbon present in a unit area of soil, typically expressed in mass per unit area (Mg ha^{-1} or kg m^{-2}) (Basile-Doelsch et al., 2023). The quantity of SOC of a given soil is a significant soil quality indicator as it plays a fundamental role in several soil functions, including improved soil fertility and productivity hence contributing to food security (Andrews et al., 2004; McBratney et al., 2014). In addition to the direct benefits of SOC, it is also a useful proxy for measuring soil health, as it tends to correlate positively with most soil properties (Mills & Fey, 2004). SOC is the most essential component in maintaining soil quality because it improves the soil's biological, chemical, and physical properties (Bhandari et al., 2002). SOC enhances the soil structure and aggregate stability, improves soil microbial biomass and soil respiration, enhances the availability of plant nutrients, improves soil water-holding capacity and cation exchange capacities, and nutrient-holding capacity (Mills & Fey, 2004; Ross et al., 2004).

2.2.3 Soil carbon sequestration

By connecting carbon transformation with the pedosphere, biosphere, and atmosphere, soil plays a critical role in the global carbon cycle. Consequently, even slight changes in the soil carbon pool will have a significant impact on atmospheric CO_2 concentrations, with potential climate change feedback (Wang et al., 2014).

Carbon sequestration is the transfer of atmospheric CO_2 into other global pools, which are long-lived, including pedologic, oceanic, biotic, and geological strata, to reduce the net rate of atmospheric CO_2 and create a C-neutral economy (Lal, 2008). Consequently, Soil carbon sequestration is defined as *"the process of transferring CO_2 from the atmosphere into the soil of a land unit through plant residues and other organic materials which are stored or retained in the unit as a part of the SOC with a long mean residence time (MRT) so that it is not re-emitted back into the atmosphere"* (Olson, 2013). Plants primarily facilitate soil carbon sequestration through the process of photosynthesis, where carbon is stored in the form of SOC. Soil carbon sequestration can also occur in arid and semi-arid areas by converting CO_2 from the air in the soil into inorganic forms such as secondary carbonates; however, the rate of inorganic carbon formation is relatively slow (Lal, 2007b). Soil carbon sequestration is a climate change mitigation technique since the carbon flux from the air to the soil may be increased while carbon release from the soil to the atmosphere can be reduced. This lowers the CO_2 levels in the atmosphere, thereby decreasing global warming and mitigating climate change. Carbon sequestration is beneficial from an environmental perspective as it removes CO_2 from the atmosphere, improves soil quality, and increases biodiversity (Batjes & Sombroek, 1997).

2.3 Measurement of SOC and SOCS calculation

2.3.1 Methods for SOC determination

There is no standardized single approach for measuring SOC. Several methods have been developed for estimating and assessing SOC concentrations, stocks, and dynamics to facilitate and ensure monitoring on a regular basis (FAO, 2017; Lorenz & Lal, 2016). The three broad methods of SOC determination include the analytical, spectroscopy, and remote sensing methods *(Table 1)*.

Table 1: Methods for SOC content determination (FAO, 2017).

Method	Name		Pros	Cons
Analytical	Wet combustion	Walkey-Black	▪ Widely used ▪ Selectively targets OM pools ▪ Little interference from carbonates	❖ Destructive ❖ Incomplete oxidation ❖ Correction factor needed ❖ Tend to underestimate SOC ❖ Environmentally unfriendly ❖ Interference from chlorides, and oxides of Mn2+ and Fe2+
	Dry combustion	Automated Carbon analyser	▪ Currently the most reliable ▪ Rapid ▪ Simple	❖ Expensive ❖ High energy use ❖ Interference from carbonates
		Loss-on -ignition	▪ Widely used ▪ Easy-to-apply method ▪ Inexpensive	❖ Not reliable (interference from carbonates or inter-lattice water) ❖ Overestimates the organic matter content ❖ SOC is derived from SOM with a conversion factor (0.58) which is known to be incorrect for organic layers
Spectroscopy	Infrared absorbance or reflectance spectroscopy: visible and near-infrared (Vis-NIR) and mid-infrared (MIR) spectroscopy		▪ Rapid ▪ Precise ▪ Cost-effective ▪ Non-destructive ▪ Used in laboratory or in the field ▪ Enables high density sampling ▪ Powerful analytical technique	❖ Continual need for calibration ❖ Soil moisture can limit the accuracy ❖ Appropriate, correct and matching reference laboratory data needed ❖ Inability to deal directly with interferences from non-SOC components in samples of unknown origin ❖ Chemometrical analysis needed
	Inelastic neutron scattering (INS)		▪ Precise and accurate ▪ Non-destructive ▪ In-field analysis ▪ High potential for the future of soil C determination	❖ Expensive ❖ Still developmental ❖ No separate measurement of SOC and Soil Inorganic Carbon ❖ Better results for C-rich soils ❖ Health hazards ❖ Interference from carbonates
	Laser-induced breakdown spectroscopy (LIBS)		▪ Precise (up to 1 mm resolution) and accurate ▪ High through-put ▪ Potential use in-field ▪ Rapid analysis	❖ Invasive ❖ Expensive ❖ Still developmental ❖ Measures total soil carbon ❖ Presence of roots and rock fragments may cause C signal variability ❖ No universal calibration curves ❖ Health hazards ❖ Interference from carbonates, iron, and water
Remote sensing	Space-borne/air-borne		▪ Used over large areas ▪ Non-destructive	❖ Limited sampling depth ❖ Surrogate indices needed

2.3.2 Calculation of SOCS

SOCS (in mineral soils) is computed as shown in equation (1), by multiplying the proportion of organic C (i.e., %C divided by 100) by the bulk density (BD), depth increment, and the proportion of coarse-fragment-free soil (i.e., < 2 mm fragments) in the depth increment (FAO, 2017; IPCC, 2003; Tadiello et al., 2022).

$$\text{SOCS} = \text{BD} * \text{D} * (\text{C}_{\text{tot}} - \text{C}_{\text{min}}) * \text{CF}_{\text{st}} \quad (1)$$

Where: SOCS = soil organic carbon stock; BD = bulk density; D = depth of horizon/depth class; C_{tot} and C_{min} = total and mineral (or inorganic) carbon content, to be considered for calcareous soils, and if dry combustion is used with typically high temperatures (otherwise: C_{tot} equals C_{min}); CF_{st} = correction factor for stoniness (1- % stones)/100), including subtraction of gravel and stones (IPCC, 2003).

The soil's bulk density, which expresses the soil weight per unit volume, is vital for estimating SOCS and is mainly responsible for the differences between estimates. The dry soil BD (bulk density) can be calculated using equation (2).

$$\text{BD} = {}^{Ms}\!/_{Vs} \quad (2)$$

Where BD = Bulk density (g cm^{-3}); Ms = Mass of dry soil sample (g); Vs = Volume of the dry soil sample (cm^3) (Tadese et al., 2023).

The determination of SOCS is rather difficult for peat soils and organic soils in general, as the area of peat, peat depth, %C, and BD are difficult to obtain (FAO, 2017; GSP Secretariat & ITPS, 2016).

Total SOCS is calculated as per equation (3) (IPCC, 2003).

$$\text{Total SOCS (Mg C ha}^{-1}) = \sum_{\text{horizon}} \text{SOC Stock}_{\text{horizon}} \quad (3)$$

2.4 Factors influencing SOCS and dynamics

SOCS is governed by factors that influence the build-up and the removal of carbon in the soil (Ahmad Dar & Somaiah, 2015). The interactions of ecosystem processes like photosynthesis, root respiration, and decomposition determine the SOC levels. SOC storage in the soil is controlled by the balance of C inputs from plant production (net primary productivity) and outputs through decomposition and soil/root respiration (Davidson & Janssens, 2006; Ontl & Schulte, 2012; Schlesinger, 1977; Trumbore, 2006). In addition to microbial decomposition, agroecosystem SOC losses can occur through soil erosion, fires, leaching, and crop biomass harvesting (Lorenz & Lal, 2018). Despite more carbon being stored in the soil than in the atmosphere and plant life combined, about a third of the world's soils face degradation, which has led to a major loss of global SOC reserves (FAO & ITPS, 2020). An estimated 50 to 70% of the antecedent SOC is lost as CO_2 through erosion, leaching, mineralization, or change in land use (Lorenz & Lal, 2005). This loss of SOC subsequently affects soil health and food production negatively and exacerbates climate change (FAO & ITPS, 2018, 2020).

The fluctuations of SOC vary in response to a number of environmental and anthropogenic driving factors (Soucémarianadin et al., 2018; Stockmann et al., 2013). The quality, quantity, and distribution of SOCS are affected by a number of environmental factors, including topography, vegetation, climate, parent material, soil texture, microbial factors, and land use (Fu et al., 2004; Wang et al., 2014). Land management and human-induced disturbances also influence the SOCS of a given landscape (Ramesh et al., 2019; Söderström et al., 2014). Understanding these factors *(Figure 1)* is essential for effective land management and harnessing soils' potential as a carbon sink for mitigating climate change.

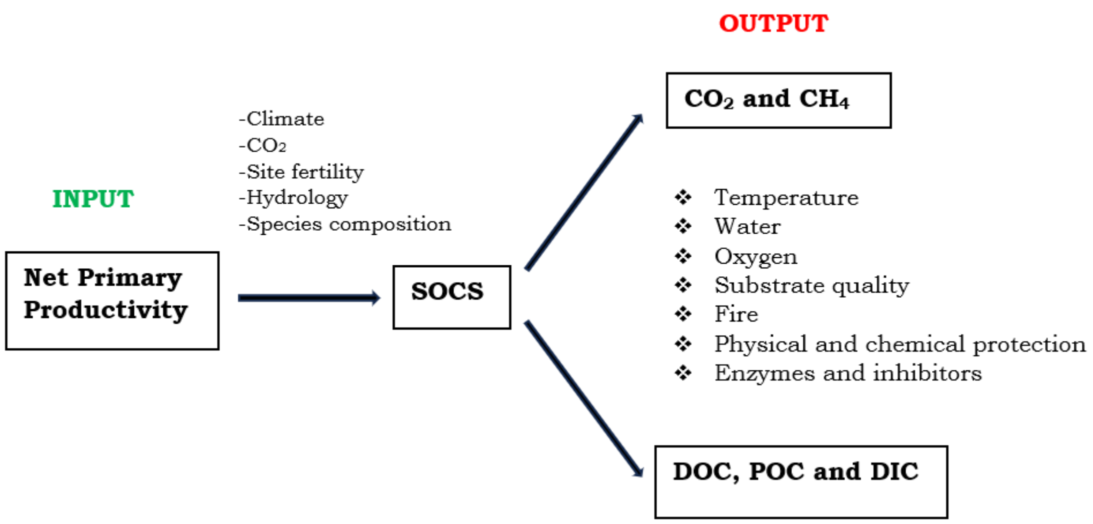

Figure 1: Factors controlling SOCS's inputs and outputs (Davidson & Janssens, 2006)

Note: SOCS = soil organic carbon stock; CO_2 = Carbon dioxide; CH_4 = Methane; DOC = dissolved organic carbon; POC = particulate organic carbon; DIC = dissolved inorganic carbon.

2.4.1 Climate

Climate, particularly temperature and precipitation, exert a significant influence on SOCS. Temperature affects microbial activity and decomposition rates, with warmer climates generally leading to increased SOC decomposition (Davidson & Janssens, 2006). Conversely, cooler regions can promote SOC accumulation due to reduced decomposition rates (Schlesinger & Andrews, 2000). Globally, SOCS generally increases with a decrease in the mean annual temperature. Regions with cold, humid climates are characterized by carbon-rich soils (Hobbie et al., 2000; Post et al., 1982). A global study established a negative correlation between soil temperature and SOC at the regional scale between 52° N and 40° S parallels, while beyond this region, a positive correlation existed (Huang et al., 2018). In the northern latitudes with cold, wet climates, the primary productivity exceeds decomposition since photosynthetic rates are not limited by moisture. However, microbial mineralization is limited by cold, resulting in high SOCS accumulation (Houghton, 2007).

Precipitation also influences SOCS through its impact on vegetation cover, soil moisture, and OM inputs and outputs since decomposition is a moisture and temperature-sensitive process (Conant et al., 2011). Well-aerated moist soils are optimal for microbial activity; hence, decomposition rates consequently decrease as soils become drier. Flooded soils (e.g., peat and muck) exhibit lower rates of OM decay due to restricted aeration, often yielding soils with very high amounts of SOC. High precipitation can also result in C leaching down the soil profile as particulate and/or dissolved OM (FAO & ITPS, 2015).

In terms of the climatic zones, the tropics have the largest carbon pool (31%), followed by the temperate zones (29%), boreal (21%), subtropics (15%), and arctic zones (3%) (FAO & ITPS, 2020). Generally, the tropics have intermediate SOC levels due to high rates of primary productivity, while the arid regions have low SOC due to low primary production. Temperate regions may experience high seasonal primary productivity and low seasonal decomposition rates, resulting in the accumulation of SOC (Huang et al., 2018). Precipitation and temperature changes can increase the SOC's vulnerability to changes over time (Follett et al., 2012). Soil organic residues and vegetation growth also vary with the temperature and precipitation conditions of various landscapes with similar land uses (Liu et al., 2011).

2.4.2 Vegetation

The type and abundance of vegetation strongly affect SOCS since both the quantity and vertical distribution of SOM are strongly influenced by vegetation (Jackson et al., 2017). The vegetation type determines the quantity and quality of litterfall and plant residues that enter the soil and the root system (Batjes & Bridges, 1994; Lal, 2004b). Plants contribute to SOC through root exudates and the decomposition of litter and OM. Due to greater organic inputs, forests and grasslands tend to have higher SOCS than croplands (Lal, 2004b, 2004a). Moreover, the quality of litter inputs, determined by plant species and their phenology, can influence SOC stabilization (Zheng et al., 2018). Generally, arid regions have low SOCS due to low primary production, while the tropics often have intermediate SOCS due to high rates of primary productivity, compensating for rapid decomposition. Some temperate ecosystems may experience seasonally high net primary productivity coupled with low decomposition rates, resulting in the accumulation of SOC (Venter et al., 2021).

2.4.3 Land use/Land cover types and changes

Land cover entails the attributes of the earth's land surface and immediate subsurface, including soil, biota, surface and groundwater, topography, and human structures, while land use encompasses the purposes for which humans exploit a given land cover (Lambin et al., 2003). Land use type affects SOM accumulation through the net primary productivity (Jackson et al., 2017). LULC change refers to changing from one type of land use or cover to another (e.g., forest to grassland, grassland to cropland). LULC changes due to anthropogenic activities may result in the degradation of terrestrial ecosystems, thereby affecting soil properties, especially SOC and total nitrogen (Wang et al., 2016). Deforestation leads to a decline in the SOC through reduced production of plant detritus, increased rates of erosion, and accelerated decomposition of OM (Schlesinger, 1977). The conversion of natural ecosystems to agricultural land coupled with increased intensity of tillage decreases the SOM levels in a given soil due to reduced inputs of OM and reduced physical protection of SOC (Davidson & Ackerman, 1993; Guo & Gifford, 2002). Conversely, successional ecosystem changes, such as reforestation, can lead to SOC recovery (Chazdon & Uriarte, 2016).

2.4.4 Soil type, properties, and depth

The composition and quantity of SOC in mineral soils strongly depend on the soil type (FAO & ITPS, 2015). Soil properties, including texture, clay content, and mineralogy, influence the SOC in a given soil (Paul, 2016). Soil texture, particularly clay content, affects SOCS by influencing water retention and microbial activity. Clay soils tend to have higher SOCS due to greater protection of OM from decomposition, while sandy soils are often characterised by lower SOC and high concentrations of alkyl C (Rumpel & Kögel-Knabner, 2011; Zhong et al., 2018). Soil pH, moisture, and redox conditions also affect SOC dynamics. Additionally, mineralogy, including the presence of iron and aluminium oxides, can influence SOC stabilization (Saidy et al., 2012). Histosols have high SOC (12–18%), while Arenosols typically have low SOC (<0.6%). Although Histosols and Chernozems are the richest soils in organic carbon, most of the global SOC is stored in Cambisols and Leptosols due to their larger area coverage (FAO & ITPS, 2020). Depth-wise, SOCS are generally higher in the surface horizons than subsurface horizons for most soils (Ali et al., 2017; Bangroo et al., 2017; Blackburn et al., 2022). Despite their low C content, the subsoil horizons contribute to more than 50% of the global SOCS and are key in the global C cycle (Rumpel & Kögel-Knabner, 2011). The relative distribution of SOC with depth is strongly associated with vegetation type (Jobbágy & Jackson, 2000).

2.4.5 Microbial communities

The magnitude of the SOC reservoir depends upon microbial involvement, as soil C dynamics are ultimately the consequence of microbial activity and growth (Liang et al., 2017). Microbial biomass and community composition can influence the decomposition rates and SOC stabilization (Paul, 2016). Factors like soil pH, moisture, and substrate availability shape microbial activity and, consequently, SOC dynamics. Microbial decomposition of biomass results in soil carbon loss as CO_2 due to respiration by microbes, while a proportion of the original carbon is retained in the soil as humus (Ontl & Schulte, 2012). The microbial community composition (bacteria and fungi ratio) may also lead to the preferential decomposition of certain compounds (FAO, 2017).

2.4.6 Landscape position and topography

Landscape position and topography influence the migration, transformation, and accumulation of SOC. Low-lying areas often accumulate SOC due to OM deposition and reduced oxygen availability (Ontl & Schulte, 2012). Conversely, elevated and well-drained areas may experience SOC loss through erosion and faster decomposition. Hillslope position (upper hillslope, middle, and lower hillslope) also significantly affects SOCS (Adiyah et al., 2022). The slope and aspect of the terrain at different elevations influence water runoff, erosion, and the accumulation of SOM.

2.4.7 Management Practices

Agricultural management practices also influence the quantity and quality of SOC and its turnover rates. Physical modification of the soil through tillage, soil compaction by machinery, and export of plant C via harvesting reduces SOC (Basile-Doelsch et al., 2023). Intensive cropping systems often result in declining yields due to reduced quality and quantity of SOC and consequent nutrient supply reduction (Bhandari et al., 2002).

On the other hand, sustainable agricultural practices, like cultivation of cover crops, agroforestry, and reduced tillage, can enhance SOCS (Poeplau & Don, 2015). The inputs of exogenous OM, like organic amendments, manure, and mineral products, including fertilizers and pH regulators, also increase the SOC (Basile-Doelsch et al., 2023).

2.4.8 Disturbances

Natural and human-induced disturbances, such as wildfires, can have immediate and lasting impacts on SOCS. Wildfires lead to rapid SOC loss through combustion and soil exposure to erosion (Doerr & Santín, 2016). Initially, fire may reduce the SOCS, but in the long run, it can result in increased SOCS through the input of very stable pyrogenic C, which positively influences plant growth (Knicker, 2007).

2.5 SOCS and its distribution

2.5.1 Global SOC and SOCS

The global SOCS varies with location as influenced by climatic factors, local geology, land use, and land management practices (FAO & ITPS, 2020). Most of the world's SOCS is stored at northern latitudes, particularly in the northern permafrost regions (~190 Pg C in the top 30 cm) due to the existing low temperatures that lead to low biological activity and slow SOM decomposition (FAO & ITPS, 2020; Scharlemann et al., 2014). Conversely, low SOCS are found in dry and hot regions such as the Sahara desert, characterised by limited plant growth (FAO & ITPS, 2020). More than 70% of the global SOCS at the top 30 cm are held by 14 countries *(*

Figure 2).

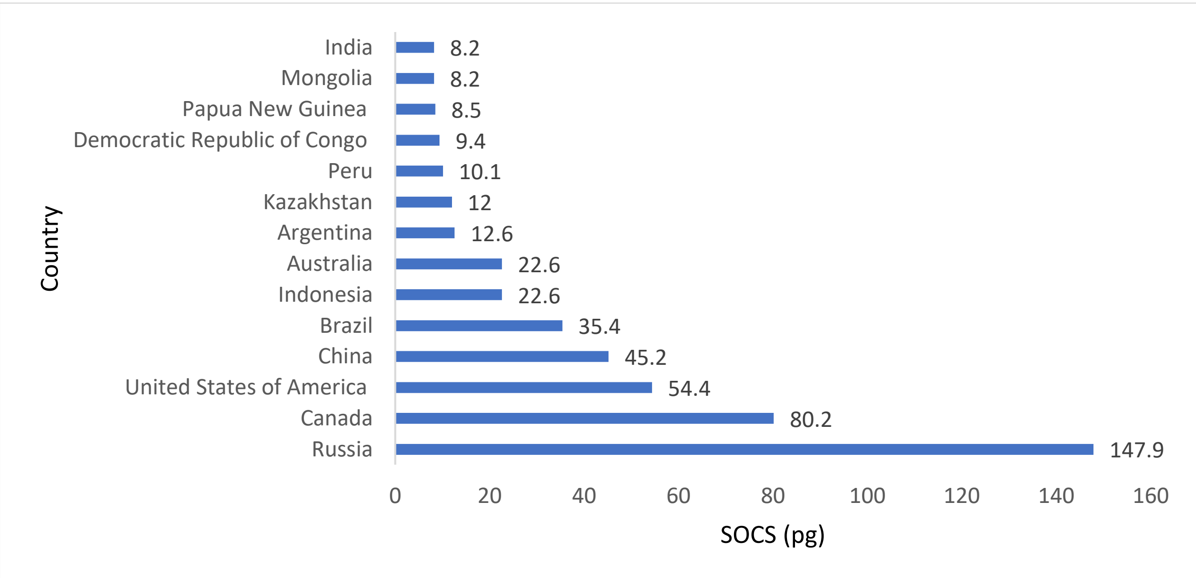

Figure 2: Top 14 countries globally with the most SOCS at the top 30 cm soil depth (Source: own creation using data from FAO & ITPS, 2020)

Out of the 14 countries, Papua New Guinea and Indonesia have the highest mean SOCS at 183.6 and 121.4 t/ha, respectively, an indication that there is a high concentration of SOCS in the tropical part of Southeast Asia and the Pacific (FAO & ITPS, 2020).

The global SOCS for the topsoil (0–30 cm) is estimated at 680 Pg of C, while the top 100 cm of the world's soils contain SOCS ranging between 1462–1548 Pg of C (Batjes, 1996; FAO & ITPS, 2020). In the tropics, SOCS is reported to range between 384–403 Pg C for the top 100 cm (Batjes, 1996). About 2400 giga tonnes of C are stored in the first 200 cm of the global soils (Minasny et al., 2017). The distribution of the world's SOCS in the top 30 cm is illustrated in *Figure 3*.

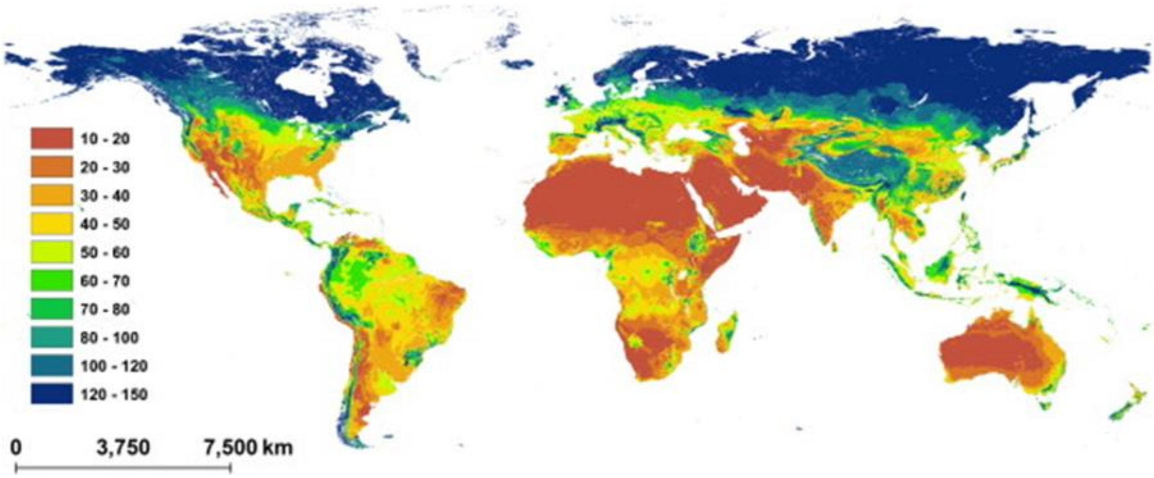

Figure 3: SOCS of the world's top 30 cm in tonne C per hectare (Minasny et al., 2017)

2.5.2 SOC and its distribution in Africa

African soils contain a significant amount of SOC distributed unevenly across the continent (*Figure 4*). High levels of SOC in Africa are largely found around the equator with the spatial variability showing a substantial gradient along the southern to the northern coasts of Africa (Kebonye et al., 2024). The wetlands and forested areas of the Democratic Republic of Congo, Rwanda, Burundi, Tanzania, Uganda, Kenya, Sudan, and Zambia have very high values of SOC (Jones et al., 2016). The African deserts on the other hand exhibit marginal SOC values (Jones et al., 2016). Both the Saharan region in northern Africa and the Kalaharian region in southern Africa have relatively lower SOC content due to their arid to hyper-arid climatic conditions which limits primary plant productivity and subsequently results in lower C inputs into the soil (Kebonye et al., 2024; Richards et al., 2023). Kebonye et al. (2024) further reiterate that SOC content across the continent of Africa is significantly and positively correlated with above-ground and below-ground plant carbon.

In the updated version of the Harmonized World Soil Database, SOCS for the continent of Africa have been estimated at 80.1 Gt C for the 0–30 cm depth and 74.5 Gt C for the 30–100 cm depth. This gives a total of 154.6 Gt C for the aggregated 0–100 cm depth (Henry et al., 2009).

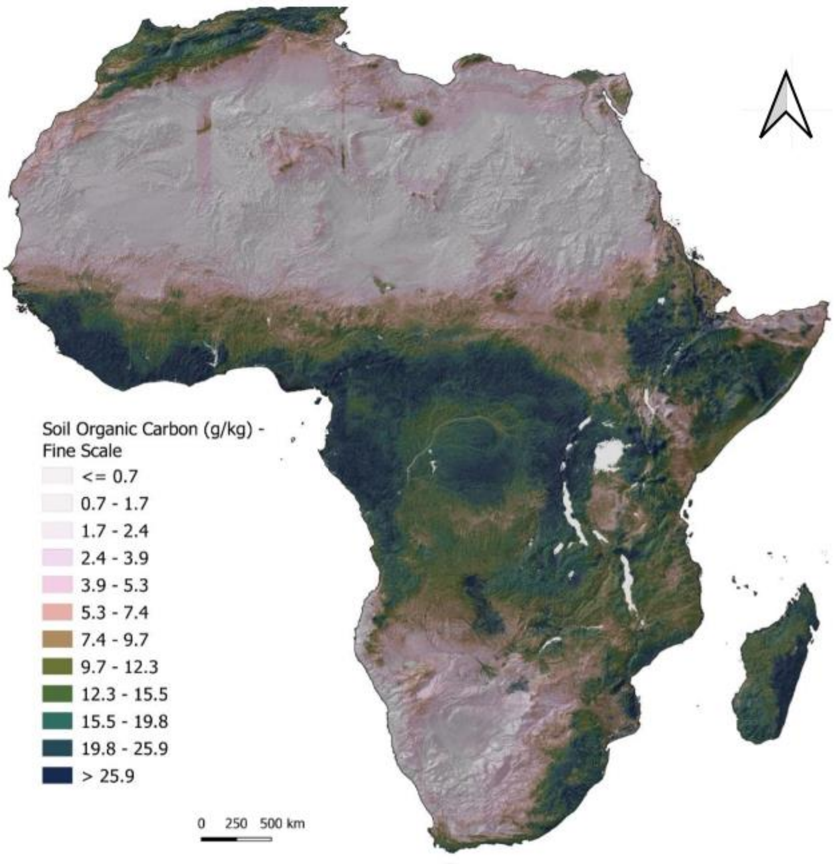

Figure 4: SOC map of Africa (Kebonye et al., 2024)

2.5.3 SOC and its distribution in Kenya

Kenya has more than 22 major soil groups (*Figure 5*) with varied regional distribution within and between different agroclimatic zones (ACZs) (Batjes, 2004; Omuto, 2013; Sombroek et al., 1982). Solonchaks, Cambisols, Luvisols, Regosols, and Ferralsols, are Kenya's top five dominant soil types in relation to the percentage extent of land area coverage (Batjes, 2004). Relatively fertile Andosols, Nitosols, Cambisols, and Phaeozems are common in the humid and sub-humid zones, while infertile Regosols, Solonetz, Arenosols, and Planosols dominate the

Arid and Semi-arid Lands (ASALs) in the eastern and northwestern regions of Kenya (Batjes, 2004).

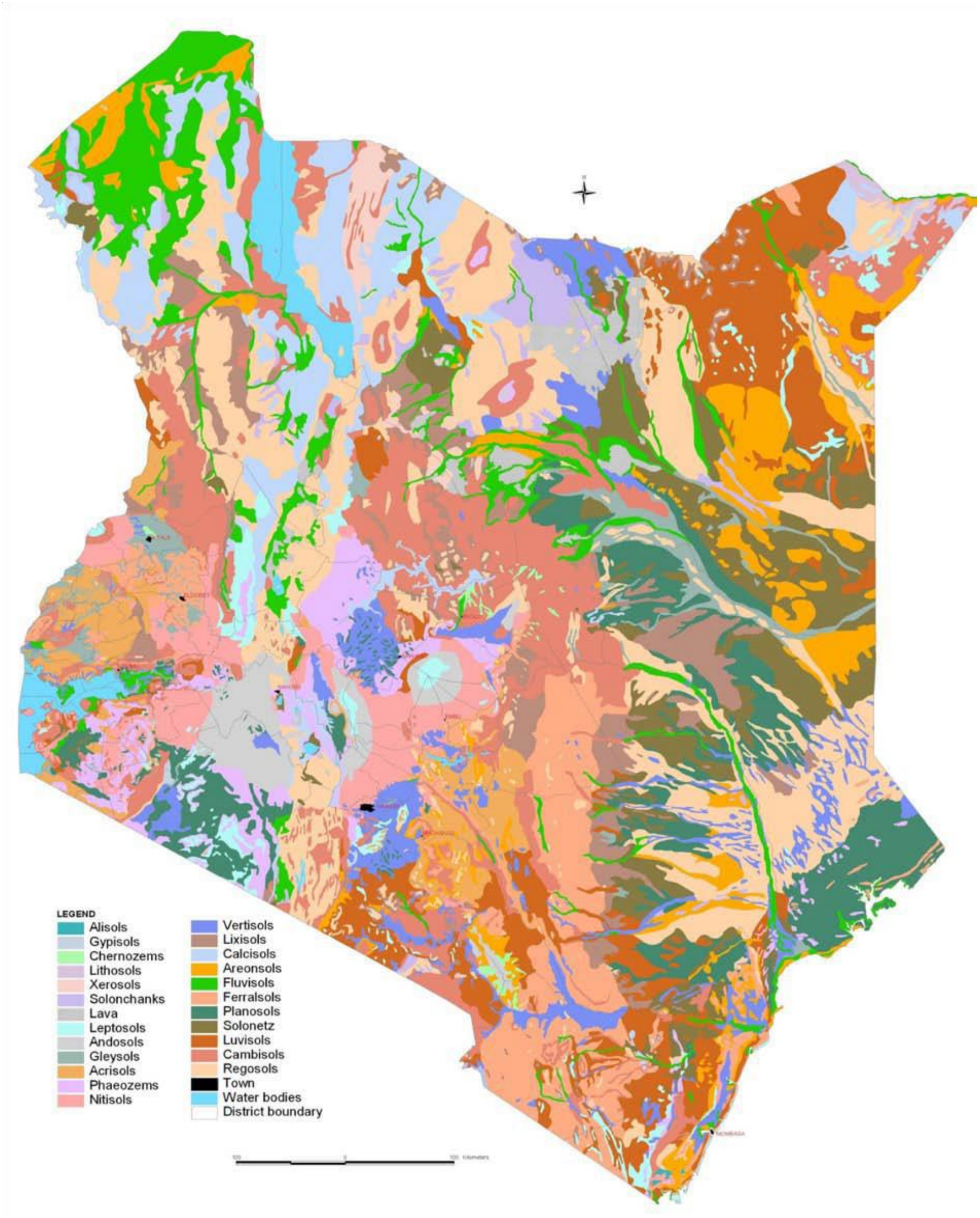

Figure 5: Map showing the major reference soil groups of Kenya (Sombroek et al., 1982)

It is estimated that Kenyan soils store approximately 2.4 Gt of C in the topsoil (0–30 cm) of the soil profile. This equals a mean SOCS of 42 Mg C ha^{-1} for the 0–30 cm depth (Minasny et al., 2017). The national estimates of SOCS to a depth of 1 m range from 3452–3797 teragrams (Tg [1 Tg = 1 million tonnes]) (Batjes, 2004). High SOC are found in Kenya's humid and sub-humid regions *(Figure 6)*, comprising the western parts of the country and the central highlands

(Batjes, 2004; Vågen et al., 2018). Whereas the Kenyan forest ecosystems make up a small proportion of the country's land area (8.83%), they are critical carbon pools and are important water towers that supply ecosystem services and goods to millions of Kenyans (Kenya Water Towers Agency, 2020; Nature Kenya, 2019; Rotich et al., 2022). The highest SOCS (>100 Mg C ha^{-1}) is located in the Kenyan forest ecosystems, including the Mount Kenya forest, Mount Elgon forest, Mau Forest Complex, Cherangany Hills forest, Aberdares forest, and Kakamega Forest (Vågen et al., 2018). The wetland ecosystems (inland riverine and palustrine areas) also form critical SOC pools in Kenya and the larger Eastern Africa region, especially in the dryland regions (Minasny et al., 2017).

On the other hand, the lowest estimated SOCS (<20 Mg C ha^{-1}) are found in the ASALs of Kenya, located in the eastern and northwestern parts of the country *(Figure 6)*. Consequently, SOC is very low (<15 g C kg^{-1}) in ASALs of Kenya (Feeney et al., 2023). It is, however, worth noting that there are pockets of relatively high SOC in parts of the ASALs of Kenya, such as the Matthews Range, and mountains such as Kulal, Marsabit, Ndoto, and Loima Hills in Turkana County (Vågen et al., 2018). These pockets represent critical SOC pools and are significant biodiversity hotspots and important resources for pastoralists for dry-season grazing (Vågen et al., 2018).

As is the case globally, the decline of SOC in Kenya has been attributed to the rapid expansion of agricultural lands and the conversion of natural vegetation into croplands (Kamoni et al., 2007; Vågen & Winowiecki, 2013). Consequently, most croplands in Kenya have been over-exploited, resulting in nutrient and OM loss (Batjes, 2004). Unsustainable agricultural practices lead to elevated rates of topsoil loss across Kenya, with an estimated mean soil erosion rate of ~5.5 t ha^{-1} yr^{-1}, equivalent to ~320 Mt yr^{-1} of topsoil lost nationwide. This translates to about ~8.8 Mt of SOC loss from Kenyan soil annually (Feeney et al., 2023). Simulation of future SOCS in Kenya using past trends and predictive models suggests that there will be a national loss of 104 Tg C from 1415 Tg in 2000 to 1311 Tg in 2030 (Kamoni et al., 2007). Improved SOCS in Kenya can be achieved through the uptake of improved agricultural management practices, the adoption of Soil and Water Conservation Practices (SWCPs) to reduce soil erosion, and the exploration of land restoration options in the affected forest ecosystems (Feeney et al., 2023; Kibet et al., 2022; Minasny et al., 2017; Were et al., 2015).

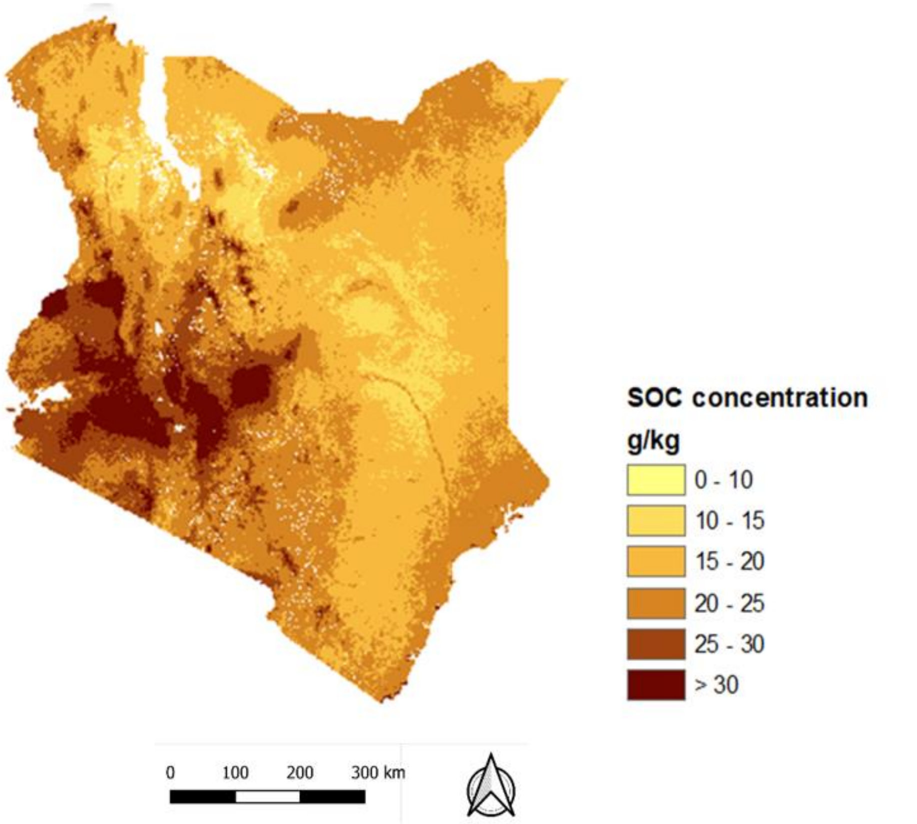

Figure 6: SOC map of Kenya (Feeney et al., 2023)

2.6 SOCS and land use

2.6.1 SOC and SOCS under different land use types

Land use patterns significantly affect the spatial variability of SOC (Dalal et al., 2021; Sun et al., 2015). SOC and SOCS are generally higher in areas with native vegetation (forestlands, shrublands, and grasslands) than in farmlands or areas with non-native vegetation under similar climatic conditions (Ayoubi et al., 2012). This is because the organic residues in the natural ecosystems are relatively higher and contain more tannin and lignin than in the farmlands, resulting in greater soil humification factors (Sattler et al., 2014; Solomon et al., 2000). About 30% of the global SOCS is stored in forested areas *(Figure 7)*, underscoring the role of forests, especially tropical forests, in carbon sequestration and accumulation (FAO & ITPS, 2020).

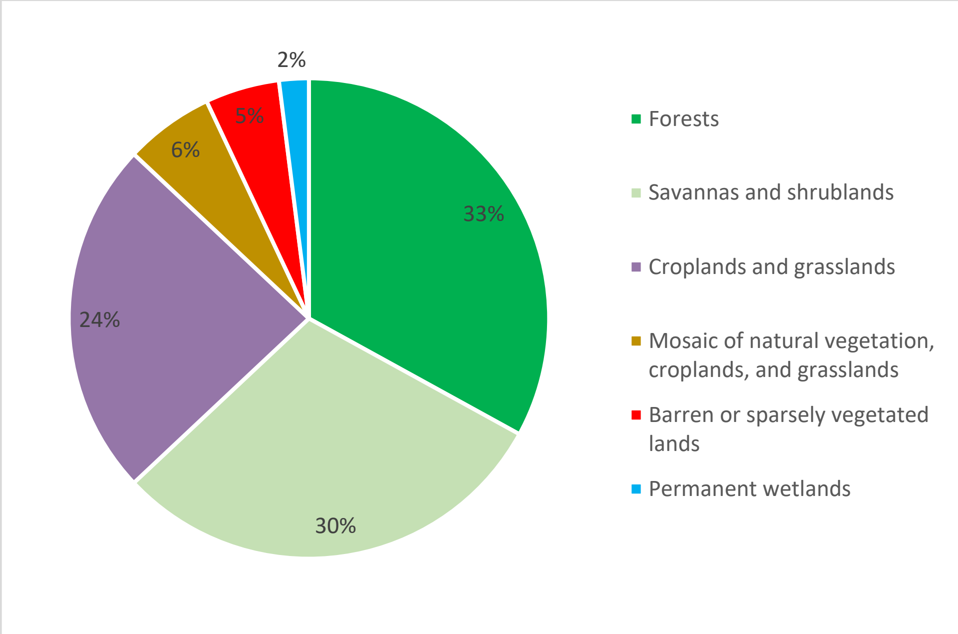

Figure 7: Global SOCS per land use/land cover type (Source: FAO & ITPS, 2020)

For any given soil type, the SOCS is determined by the balance of net C inputs to the soil as OM and net C losses from the soil as CO_2, dissolved organic C, and soil erosion (Ahmad Dar & Somaiah, 2015; Smith, 2008). LULC largely determines the C inputs to the soil, with forest ecosystems having the largest and the most recalcitrant input of C to the soil throughout the year. Grasslands also have large inputs, though the C input in grasslands is less recalcitrant in comparison to the forest litter. The smallest and most labile C input is usually found in croplands, as inputs are only present when there is a crop growing on the farm (Smith, 2008). This small input is reduced upon biomass removal in the harvested crops and can be further exacerbated by the removal of crop residue for other uses. Tillage of croplands also accelerates SOC depletion by breaking open soil aggregates, exposing protected organic C to microbial breakdown and weathering. Undisturbed land use types like natural forests generally improve SOC storage, soil structural stability, and aggregation, reducing C emission and soil erosion, especially in mountainous regions (Ayoubi et al., 2012).

A survey of the mountainous landscapes in southwestern Yunnan province, China, indicated that SOM content decreased in the topsoil among different land use types in the order of forestland > scrubland > grassland > farmland (Liu et al., 2015). In the North-eastern Himalayan Region of India, non-agricultural land uses of forests and grasslands had significantly higher SOC (2.20 to 2.51%) and SOCS (35.2 to 42.1 Mg C ha^{-1}) compared with agricultural, horticultural, and plantation land uses (SOC, 1.44 to 1.63%; stock, 27.4 to 28.4 Mg C ha^{-1}) (Choudhury et al., 2016). A study in the Eastern Mau Forest Reserve of Kenya also showed significant variations of SOC and total nitrogen (TN) stocks under different land use types like natural forests, plantation forests, bamboo forests, and croplands (Were et al., 2015). The study by Were et al. (2015) examined SOCS variation under different land cover types and soil depths in the Mau Forest using a completely randomized sampling design, the influence of elevation and soil management practices on SOCS was not covered. This informed the current study as it aims to bridge the gap by going a step further to incorporate elevation gradient and RSMPs as potential factors influencing SOCS.

2.6.2 Impacts of LULC changes on SOC and SOCS

Different land use types often influence SOC and SOCS and have been reported to differ with the change in land use types. This is largely due to the combined effect of chemical and biophysical processes over time (Post & Kwon, 2000). Changes in land use influence the quantity and rates of SOC losses and gains (Korkanç, 2014; Solomon et al., 2000). The SOC tends to be lost when forests, grasslands, and other natural ecosystems are converted into croplands or when highly organic soils are drained, cultivated, or limed (Smith, 2008). About 50% of the global vegetated land surface is estimated to be converted to croplands, rangeland, and pastures (Bondeau et al., 2007; Feddema et al., 2005). Agricultural expansion-related land cover changes and deforestation rank among the largest global sources of anthropogenic carbon emissions and SOCS loss (Baccini et al., 2012; Smith, 2008). Changes in land use and agricultural expansion have contributed 136 ± 55 Pg of C to the atmosphere since the start of the industrial revolution, with SOC depletion accounting for a further contribution of about 78 ± 12 Pg C (Zomer et al., 2017).

On the other hand, SOC can build up when agricultural land is restored back to forestland, grasslands, or native vegetation or when organic soils are restored back to their native condition (Post & Kwon, 2000; Smith, 2008). Land use change from agriculture to forestry implies that the short annual crop cultivation and harvesting cycle is replaced by a much longer forest cycle, which allows for the accumulation of a larger biomass and reduces the level of soil disturbance (Vesterdal et al., 2002). Afforestation of semi-arid and degraded lands reduces erosion and also results in improved soil properties, including SOC (Korkanç, 2014). A meta-analysis of the effects of afforestation on SOC storage in Canadian border provinces and the U.S.A states revealed that land conversion to forest increased SOC by 21% (Nave et al., 2013). Stopping the conversion of natural ecosystems to agricultural lands would be the most efficient way to reduce SOC loss globally. Best land management practices that increase soil C inputs and reduce soil losses can also help to maintain or increase SOC (Lal, 2001; Smith, 2008; Solomon et al., 2000).

2.6.3 Land use land cover types and changes in Kenya

Kenya has different LULC classes, including rangeland, cropland, forest, wetland, barren land urban/built-up and water (*Figure 8*). Rangelands (shrubland and grassland) dominate about 70% of the total land cover in Kenya. Croplands are the second most dominant LULC type at 11.40% of the total land area, while forests make up 8.83% of the land cover. Wetlands, built up, water and barren land comprise the remaining 9.77% of the land area (Kenya Forest Service, 2021; Ministry of Environment and Forestry, 2020). Kenyan croplands are mainly located in the western and central parts of the country (*Figure 8*), while most of the forests in Kenya comprise the montane forests and dryland forests (Feeney et al., 2023; Kenya Forest Service, 2021).

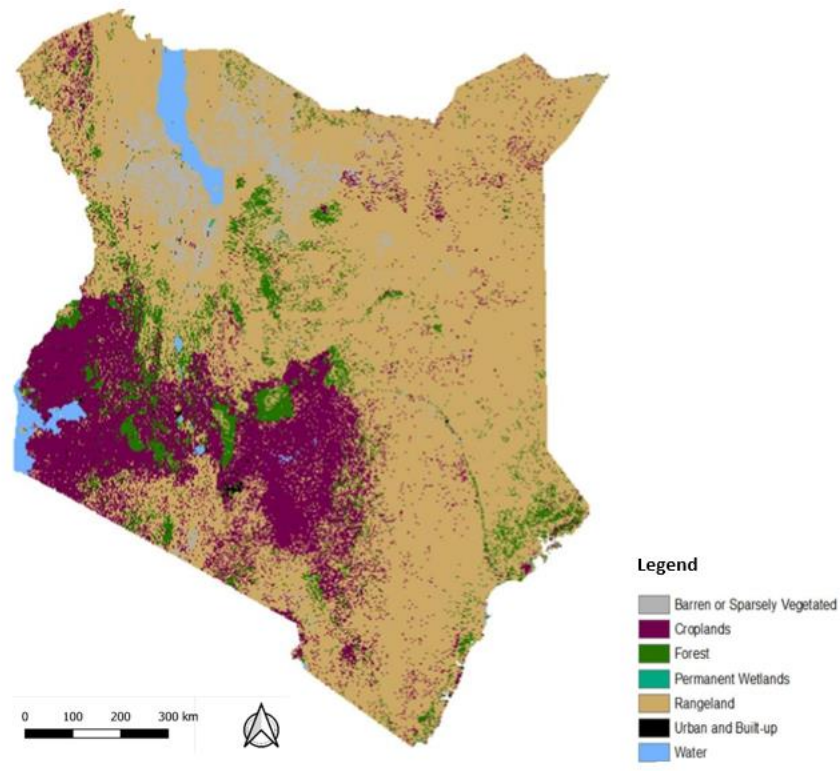

Figure 8: Land use/land cover map of Kenya (Feeney et al., 2023)

The various land use types have experienced changes over time *(Table 2)*. Forestlands have reduced from 6.2% to 5.8%, while croplands have slightly increased from 8.9% in 2002 to 11.4% in 2018. Kenya has experienced increased conversions of natural ecosystems (forests, grasslands, wetlands) to croplands in the recent past due to increased demand for food production to cater to the expanding population (Bullock et al., 2021; Kipkulei et al., 2022; Rotich & Ojwang, 2021). The central Kenya region has undergone significant changes in land cover due to population density, with notable conversions of forestlands to other land use types (Mwangi et al., 2020). At the foothills of Mount Kenya, both irrigated and rainfed croplands have expanded over time at the expense of natural habitats, including protected areas (Eckert et al., 2017; Kariuki, 2006). Most of the agricultural expansion in central Kenya occurred in the 1980s and 1990s, whereas agricultural intensification largely happened after 2000 (Eckert et al., 2017). Deforestation, due to agricultural expansion and intensification, characterizes recent land use developments on the eastern slopes of the Mt. Kenya region (County Government of Tharaka Nithi, 2018; Willkomm et al., 2016). The conversion of forests to croplands undermines the ecosystem's capacity for carbon sequestration (Were et al., 2015). The expansion of agricultural land areas at the expense of natural habitats is, therefore, likely to accelerate soil erosion, thereby resulting in losses of SOC and other soil nutrients (Feeney et al., 2023).

Table 2: Kenya's land use land cover statistics from 2002 to 2018 (Ministry of Environment and Forestry, 2020).

Land use	**2002**		**2006**		**2010**		**2014**		**2018**	
	Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Dense forest	2,057,649	3.5	2,139,703	3.6	2,463,674	4.2	2,558,363	4.3	2,205,189	3.7
Moderate forest	1,021,083	1.7	657,767	1.1	889,327	1.5	609,436	1.0	816,174	1.4
Open forest	591,035	1.0	522,508	0.9	525,469	0.9	415,061	0.7	441,173	0.7
Total Forests	3,669,768	6.2	3,319,978	5.6	3,878,470	6.6	3,582,861	6.1	3,462,536	5.8
Wooded grassland	33,447,438	56.5	32,286,628	54.5	31,742,295	53.6	32,388,566	54.7	32,271,452	54.5
Open grassland	8,985,269	15.2	9,299,024	15.7	9,331,841	15.8	8,821,893	14.9	8,980,656	15.2
Total Grassland	42,432,707	71.7	41,585,652	70.2	41,074,136	69.4	41,210,459	69.6	41,252,109	69.7
Perennial cropland	281,775	0.5	299,776	0.5	261,821	0.4	299,727	0.5	284,357	0.5
Annual cropland	4,995,761	8.4	5,798,968	9.8	5,800,963	9.8	5,901,652	10.0	6,455,816	10.9
Total cropland	5,277,516	8.9	6,098,743	10.3	6,062,784	10.2	6,201,378	10.5	6,740,173	11.4
Vegetated wetland	29,327	0.0	40,541	0.1	45,956	0.1	38,868	0.1	40,212	0.1
Open water	1,212,707	2.0	1,177,785	2.0	1,215,342	2.1	1,223,689	2.1	1,227,320	2.1
Total wetland	1,242,034	2.1	1,218,326	2.1	1,261,298	2.1	1,262,557	2.1	1,267,532	2.1
Settlements and Other land	6,581,764	11.1	6,981,089	11.8	6,927,099	11.7	6,946,533	11.7	6,481,438	10.9
Grand total	**59,203,788**	**100**	**59,203,788**	**100**	**59,203,788**	**100**	**59,203,788**	**100**	**59,203,788**	**100**

2.7 Elevation and SOCS

2.7.1 Variation of SOCS along an elevation gradient

Elevation can be used as a simple and effective predictor of SOCS (Tsui et al., 2013). Previous studies have reported increased SOCS with increasing elevation (Du et al., 2014; Garten & Hanson, 2006; Tashi et al., 2016; Tsozué et al., 2019), a decreasing SOCS trend with the increase in elevation (Bangroo et al., 2017; Kilonzo et al., 2023; Shaheen et al., 2017; Sheikh et al., 2009), while others found no relation between SOCS with elevation (Phillips et al., 2019; Zimmermann et al., 2010). These variations in SOC concentrations and stocks can be attributed to altitudinal gradient-driven differences in climatic elements (rainfall and temperature), vegetation types, and soil properties (pH, bulk density, depth) (Choudhury et al., 2016; Dieleman et al., 2013; Njeru et al., 2017).

In tropical mountain ecosystems, it is well established that altitude-driven agroecological factors like temperature, precipitation, and vegetation cover are significant influencers of SOCS and TN stocks (Njeru et al., 2017; Zech et al., 2014). An increase in elevation in most cases corresponds to a decrease in temperature, which in turn leads to reduced rates of OM decomposition, thereby inducing the accumulation of SOC (Choudhury et al., 2016; Phillips et al., 2019). A study carried out in the Mount Bambouto region of Central Africa revealed an increase in SOCS along the elevation gradient (Tsozué et al., 2019). This pattern was attributed to longer vegetative growing periods at high altitude zones with minimal human interference in comparison with the lower altitude zones (Tsozué et al., 2019). SOC variations in the fragile hilly ecosystem of the northeastern Himalayan Region of India were mainly due to variations in climatic elements (rainfall and temperature) driven by altitudinal gradients and soil silt and clay contents (Choudhury et al., 2016). Analytical results of a study conducted in the Tsegede highlands of Tigray region, northern Ethiopia, showed a significant correlation between OM and elevation. The SOM content of the lower elevation site was lower by about 43% compared to SOM in the high elevation site (Kidanemariam et al., 2012).

On the other hand, the increase of SOC as altitude decreases may be due to a higher vegetation diversity, better stabilization of SOC, and the deposition of eroded SOM at lower altitudes (Shaheen et al., 2017; Sheikh et al., 2009). Lower altitudes can have favourable micro-climatic conditions which favour increased vegetation productivity due to the higher species diversity (Kilonzo et al., 2023). Reduced erosion as a result of more level slopes at the lower altitudes combined with the deposition of eroded SOM from the steeper higher elevations all contribute to the accumulation of SOCS (Naftaly et al., 2022).

Lack of topographic variations for SOCS can be caused by the similar vegetation types, soil properties and management practices along the toposequence (Simon et al., 2018; Tian et al., 2020). Less variations in soil properties like texture and moisture retention often play a more dominant role than elevation in determining SOC levels (Tan & Lal, 2005). Uniform vegetation cover and management practices could also lead to similar SOC levels across elevation gradients, even in regions with varying topography (Dhaliwal et al., 2019).

2.7.2 Description of Kenya's elevation gradient

The geography of Kenya is very diverse. The elevation ranges from the low-lying coastal lowlands of Mombasa, located in the southeastern part of the country at 0 m above the sea level, to the Kenyan highlands, peaking at Mt. Kenya's 5,199 m above sea level in central Kenya (*Figure 9*). The Great Rift Valley (GRV), in the western and central part of Kenya, separates the Kenyan highlands into the eastern and western highlands. As you move further west, the altitude decreases towards Lake Victoria, while northwards, there are vast drylands that are gradually being colonized to support livelihoods for the pastoralist communities and game ranchers (Ministry of Environment and Forestry, 2020). Most Kenyan montane forests characterised by high SOCS are found in the Kenyan highlands, which are in the central and western parts of the country.

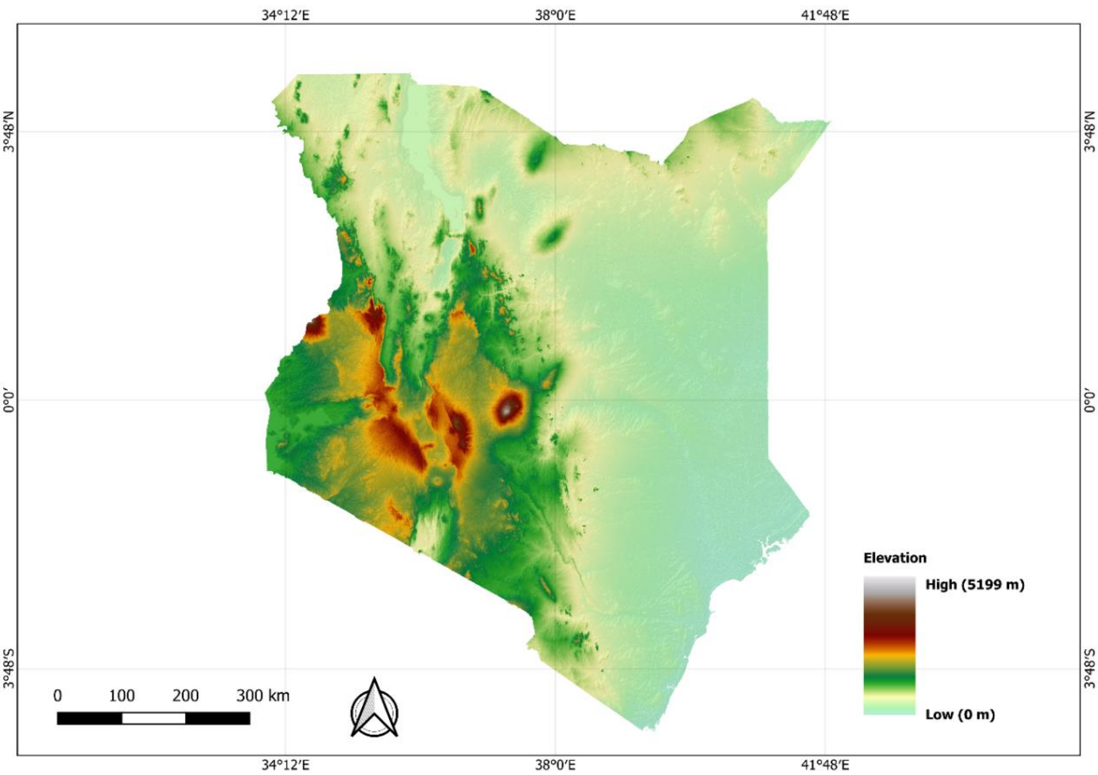

Figure 9: Map showing the elevation of Kenya (Source: author)

2.8 SOCS and Recommended Soil Management Practices

To determine future carbon fluxes and create the most effective management plans to slow and even reverse soil loss, an understanding of the impact of management practices on SOCS is necessary (Jackson et al., 2017). It has been established that certain Recommended Soil Management Practices (RSMPs) reduce soil losses, increase carbon inputs, and facilitate the build-up of SOM or increase the stabilization of organic residues in the soil, thereby enhancing the SOCS and sequestration rates (Kane, 2015; Lal, 2009; Minasny et al., 2017; Paustian et al., 2016). These RSMPs are built on the principles of conservation agriculture comprising minimum mechanical soil disturbance, permanent soil organic cover with crop residues and/or cover crops, and crop diversification through rotations (Francaviglia et al., 2023). RMSPs can be broadly grouped into agronomic practices (cover crops, mulching, crop rotation, minimum tillage, manure application, contour farming) vegetative practices (agroforestry, strip cropping, intercropping, windbreaks) and structural practices (terraces, ditches, stone bunds, contour bunds) (Gachene et al., 2020; Rotich et al., 2022).

The most appropriate RSMPs for increased SOCS within croplands must be site-specific and directed towards increasing SOM inputs and decreasing OM decomposition (Batjes, 2004). Research has shown that RSMPs can increase SOCS on agricultural and other lands with low SOCS through practices like agroforestry, conservation tillage, cover cropping, the addition of organic manures, and mulching (Lal, 2016; Paustian et al., 2016; Zomer et al., 2017).

2.8.1 Agroforestry

Agroforestry involves farming practices that combine agricultural crops and/or animals with trees/shrubs on the same piece of land (Kinama et al., 2007). In silvo-arable systems, trees are intercropped with arable crops, while in silvo-pastoral systems, trees are combined with pastures for livestock (Cardinael et al., 2017). In addition to acting as a source of income for smallholder farmers, agroforestry practices significantly contribute to climate change mitigation by sequestrating C in soil and vegetation (Lorenz & Lal, 2014; Nair, 2011). The amount of SOC in agroforestry systems varies with regions, agroforestry systems in practice, and soil depths (Agevi et al., 2017). It is estimated that the SOCS in agroforestry systems globally may amount to up to 300 Mg C ha^{-1} to a depth of 100cm (Lorenz & Lal, 2014). In tropical regions, the C sequestration potential of agroforestry systems is estimated between 12 and 228 Mg C ha^{-1} with a median value of 95 Mg C ha^{-1} (Albrecht & Kandji, 2003).

Agroforestry trees modify the quantity and quality of the above and below-ground litter and modify microclimatic conditions, including the soil temperature and moisture regimes (Cardinael et al., 2017; Laganière et al., 2010). The C is stored in the trees' aboveground and belowground biomass, and the transfer of OM to the soil from leaf litter and pruning residues can increase SOCS both in tropical and temperate regions (Albrecht & Kandji, 2003; Cardinael et al., 2017). The extensive root systems of agroforestry trees can grow deep into the mineral soil thereby acting as sources for the SOC pool in deeper soil horizons (Kell, 2012). Incorporating nitrogen-fixing trees in agroforestry systems may result in higher biomass production and, thus, improved SOC sequestration and C pools, particularly in deeper soil horizons (Lorenz & Lal, 2014).

A study in the temperate agroforestry systems of Belgium showed that agroforestry trees significantly increased SOC and nutrient availability in 17 arable agroforestry fields (Pardon et al., 2017). A survey of six different agroforestry sites in France showed increased SOCS under agroforestry systems, further highlighting the potential of agroforestry systems to store C in both soil and biomass in temperate ecosystems (Cardinael et al., 2017). Research carried out in western Kenya showed greater SOCS in lands under agroforestry compared to grazing land and cropland at different soil depths (Kibet et al., 2022).

2.8.2 Minimum tillage

Different tillage methods have different outcomes on soil health and crop production (Githongo et al., 2021). Conventional tillage practices often destroy the soil structure and cause compaction in the case of farm machinery use. This negatively affects soil aeration, root development, and water infiltration, in addition to exposing SOM to decomposition (Gachene et al., 2020). Minimum tillage or reduced tillage, on the other hand, minimizes soil disturbance save for the planting stations (Githongo et al., 2021; Ngoma et al., 2015). Soils under minimum tillage, therefore, remain largely undisturbed, leaving the soil aggregates intact, thereby physically protecting SOM. Through reduced soil erosion, minimum tillage augments the soil's physical, chemical, and biological properties hence allowing for SOM buildup (Cardoso et al., 2013). Minimum tillage can alter the profile distribution of SOC by concentrating it in the topsoil (Luo et al., 2010). It also reduces soil compaction, decreases erosion and runoff, and helps conserve soil microbial activity by enhancing the protection of SOM from hastened decomposition, leading to the restoration of soil biological processes (Sauvadet et al., 2018). Several studies have demonstrated that minimum tillage has the potential to increase SOC rapidly, especially at the topsoil (Githongo et al., 2021; Kane, 2015; Sauvadet et al., 2018).

2.8.3 Mulching

Mulching entails the use of crop residues or other materials as mulch primarily for soil moisture conservation and control of soil erosion (Mulumba & Lal, 2008). The mulch decreases the surface runoff velocity, thereby improving water infiltration capacity and reducing SOM loss from erosion (Gachene et al., 2020). Mulching also protects the soil surface against splash erosion by reducing the raindrop impact (Mulumba & Lal, 2008). The use of crop residue as mulch increases SOC upon decomposition thereby maintaining or enhancing the soil quality and productivity (Saroa & Lal, 2003). Mulching also enhances the burrowing activity of earthworms, which in turn increases the percolation of water through the soil profile. This increases the soil moisture storage in the root zone. An experimental research in the Ohio State of the United States of America (USA) showed that mulch application positively affected select soil physical properties, including increased total porosity, soil aggregation, available water capacity, and moisture content at field moisture capacity (Mulumba & Lal, 2008). Integrated use of mulching and contour hedgerows in a sloping semi-arid land of Eastern Kenya remarkably reduced runoff from 100 mm to 20 mm and soil loss from 100 to 2 Mg ha^{-1} (Kinama et al., 2007).

2.8.4 Organic amendments

In the majority of smallholder farming systems in the tropics, organic resources are essential for maintaining SOM over the long run as well as for short-term nutrient availability (Palm et al., 2001). The addition of organic manure in the soil plays an essential role in soil fertility management as it helps in the augmentation of soils. It positively influences the long-term formation and maintenance of SOM, improves the supply of plant nutrients, and improves the plants' nutrient use efficiency (Lazcano et al., 2013; Palm et al., 2001). A meta-analysis of literature from Sub-Saharan Africa shows that animal manure positively influences SOC content (Githongo et al., 2021). Other emerging alternative organic fertilizers include vermicompost and biochar. Vermicompost stimulates soil microbial growth and activity and the subsequent mineralization of soil plant nutrients, while the incorporation of biochar in soil improves soil C sequestration and the retention of soil nutrients, such as nitrogen (Jouquet et al., 2011; Vaccari et al., 2011).

2.8.5 Cover crops

Cover cropping involves the growing of annual, biennial, or perennial crops as a monoculture or polyculture to improve soil quality, conserve soil moisture, regulate soil temperature, control weeds and pests, reduce soil erosion, and improve soil biodiversity (Lu et al., 2000). Keeping the soil covered is the fundamental principle of cover cropping which protects the soil against splash erosion. Biomass and litter from the cover crops increase the soil surface residue, thereby providing additional SOM that improves soil structure and quality (Karuku, 2018; Lu et al., 2000). The degree of SOC addition from cover crops ranges from 0.27 to 1.03 t C ha^{-1} yr^{-1} and varies with the type of cover crop used, the climatic conditions in a region, and the specific management practices applied (Francaviglia et al., 2023). The use of legumes as cover crops helps fix nitrogen in the soil and thus contributes to the nitrogen requirements of subsequent crops (Lu et al., 2000). Cover crops have been used in Kenya for centuries to improve soil quality, control soil erosion, reduce nitrogen leaching, and repel insects (Mwangi et al., 2015). Cover crops can also be harvested and used for animal feed or biofuel production (Wawire et al., 2021).

Common cover crops in Kenya include legumes such as beans (*Phaseolus vulgaris*), pigeon peas *(Cajanus cajan)*, Cowpeas (*Vigna unguiculata*), velvet bean (*Mucuna pruriens (L.) DC*), lablab (*Lablab purpureus L.*), and hairy vetch (*Vicia villosa*) among others (Karuku, 2018; Mwangi et al., 2015).

2.8.6 Challenges and limitations in implementing RSMPs

Despite the benefits associated with these practices, the adoption level is still low, especially in developing nations, due to implementation challenges. The low farmer adoption can be linked to environmental, economic, institutional, and social constraints (Baveye et al., 2018; Francaviglia et al., 2023; White et al., 2018).

Local pedoclimatic conditions, including soil type, precipitation amounts and distribution, and temperature conditions, can limit the application of some management practices (Francaviglia et al., 2023). Most smallholder farmers, especially in Africa, lack the necessary resources (insufficient manure because of lack of farm animals) or have competing uses of crop residues and animal dung (Lal, 2009). Additionally, the implementation of some RSMPs is uneconomic for farmers (Poulton et al., 2018). The lack of financial incentives and/or subsidies to motivate farmers or compensate them for possible yield losses inhibits the adoption of these practices in many regions globally (Francaviglia et al., 2023). Other factors that hinder the adoption of RSMPs include the unavailability of labour, small farm sizes, lack of access to cash and credit facilities, insecure land tenure, and limited agricultural extension support from the government (Belayneh, 2023; Degfe et al., 2023; Lal, 2009; Ojo et al., 2021; Tiwari et al., 2008; Yifru & Miheretu, 2022).

Financial viability is a major determinant in persuading farmers to change farming practices from traditional farming practices to adopt more carbon-friendly farming practices. Efforts should be made toward the development of policies and related incentives to encourage the adoption of RSMPs (Rumpel et al., 2020). Adequate training and extension services should also be provided to farmers to help them with the implementation (Francaviglia et al., 2023).

3. MATERIALS AND METHODS

This section describes the study areas' geographical location, topography, climate, geology, soils, biodiversity, water resources, land use, demographic, and socio-economic characteristics. Subsequently, the sampling design and the criteria used in determining sampling locations, as well as the methods and procedures used in collecting soil samples and social data, are detailed in this section. Finally, the laboratory analyses protocols and statistical analyses used for the soil and social data are also elaborated in this section.

3.1 Study area

3.1.1 Description of the study area

This study focused on Tharaka Nithi County (TNC), located on the eastern slopes of Mount Kenya in central Kenya (*Figure 10*). TNC covers an estimated area of 2,564.4 km^2 within longitudes 37°19′ and 37°46′ East and latitudes latitude 00°07′ and 00°26′ South (County Government of Tharaka Nithi, 2023; Kenya National Bureau of Statistics, 2019).

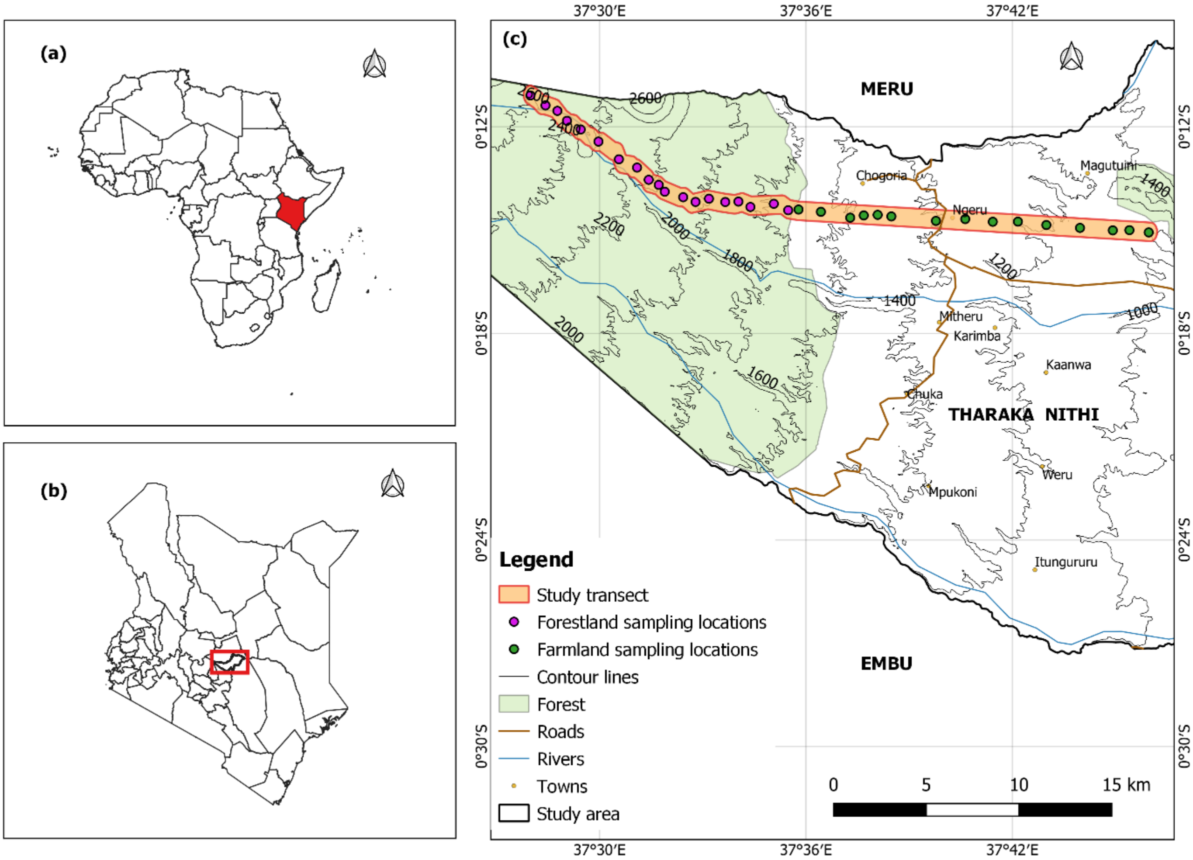

Figure 10: Map of the study area showing (a) The location of Kenya in Africa, (b) The location of the study area in Kenya, (c) The study transect and sampling locations on the eastern slopes of Mount Kenya. (Source: author)

3.1.2 Topography

The elevation of TNC *(Figure 11)* ranges from 600 m asl Eastwards in the ASALs of Tharaka to about 5199 m asl at the snowcapped peak of Mt Kenya *(Figure 11)*. This unique altitudinal gradient of TNC leads to a varied range of ecosystems in a relatively small area making the region ideal for this kind of study. TNC generally has a rugged and hilly terrain. The major hills found in the county landscape include Munuguni, Kiera, and Njuguni in the Maara constituency, while Gikingo, Kijege, and Ntugi hills are found in the Tharaka constituency (County Government of Tharaka Nithi, 2018). The topography of TNC is greatly influenced by the volcanic activity of Mt. Kenya, creating 'V' shaped valleys from which the tributaries of River Tana originate as they flow eastwards (County Government of Tharaka Nithi, 2023).

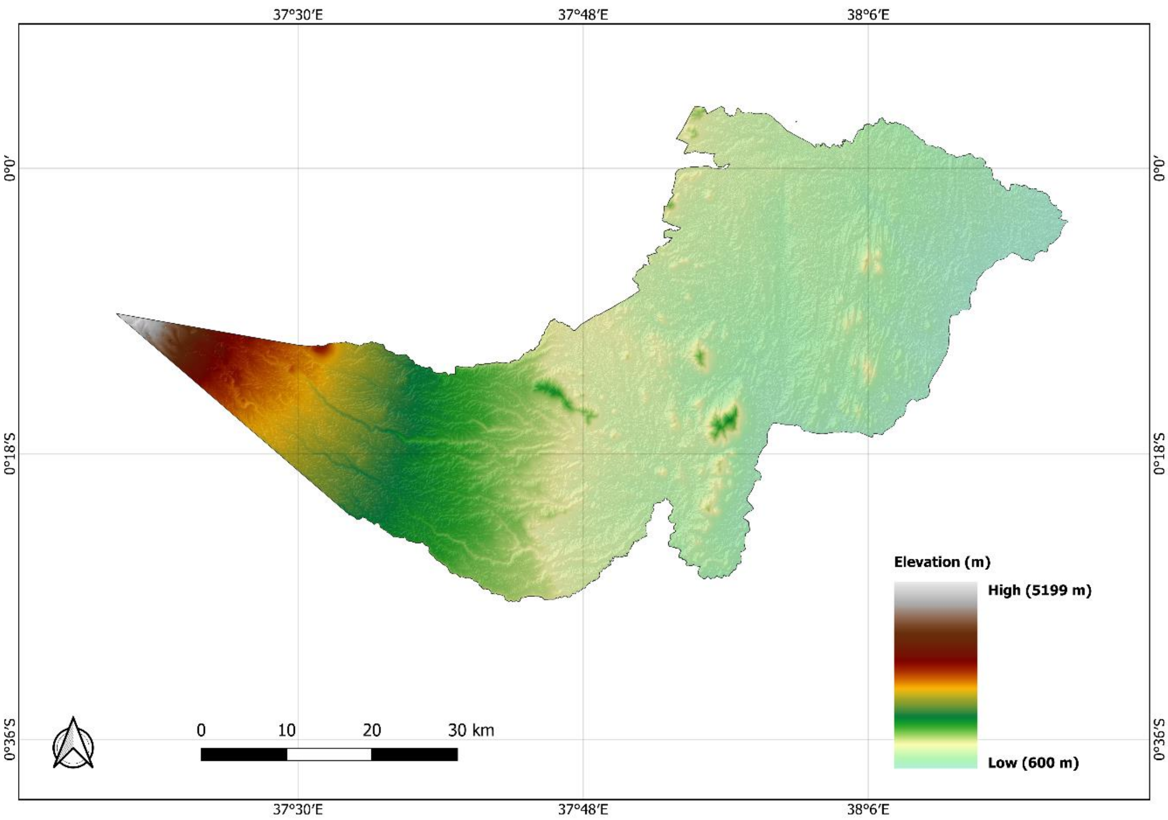

Figure 11: Map showing the elevation of the study area (Source: author)

3.1.3 Geology

The study area's geologic composition mainly comprises volcanic rock, volcanic ash, and some old metamorphic rocks *(Figure 12)*. The volcanic rocks found in the area are related to the Rift Valley development during the Pliocene time which dates back 2 to 3.5 million years. There are three distinguished phases of deposition by this volcanism (Schoeman, 1952). The first phase occurred during the main activity of Mt. Kenya, where phonolite flows and lahars were deposited in the area during the upper Pliocene time. The second phase was during the activity of the parasitic cones in the northeastern side of Mt. Kenya during the Plio-Pleistocene time (Schoeman, 1952). The third and most recent phase was during the Pleistocene time, which is related to the activity of the parasitic cones of Mt. Kenya. *Lahar, tuffs,* and *volcanic ashes* were deposited during the time, especially in the river valleys. The volcanic rocks related to the Mt. Kenya series are, therefore, mainly composed of lahars, phonolites, tuffs, basalt, *and volcanic ashes* (Schoeman, 1952).

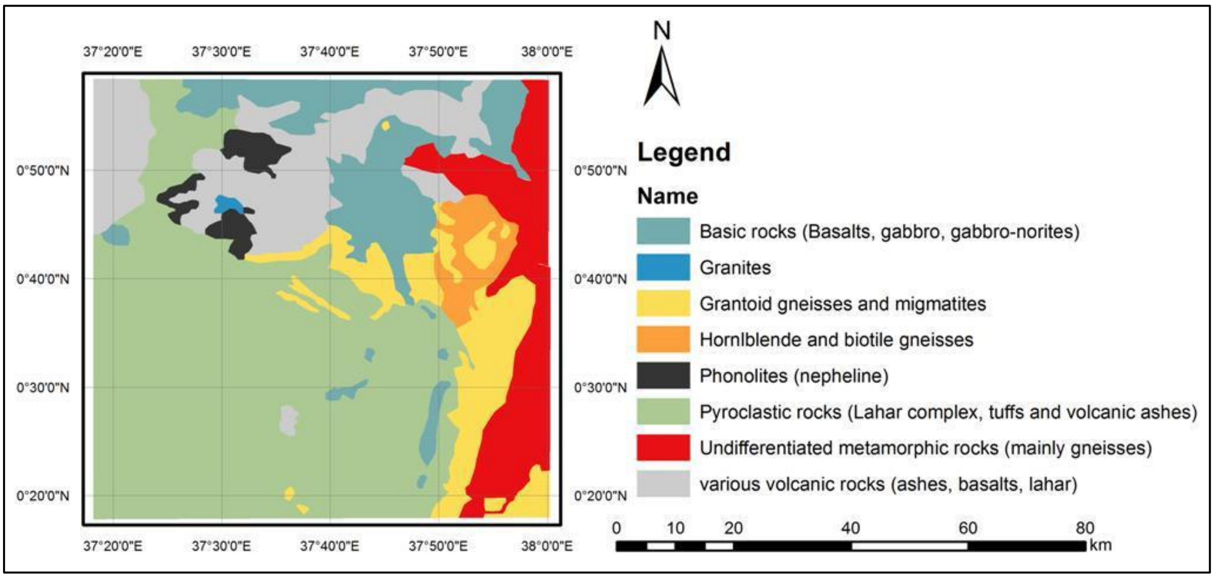

Figure 12: Spatial distribution of rocks comprising the parent material of the study area's soils (Mutuma, 2017).

3.1.4 Soils

The dominant WRB (IUSS Working Group WRB, 2015) Reference soil groups (RSG) in the study area include Histosols, Nitisols, and Andosols (Dijkshoorn, 2007). The upper forested slopes of the study area are humid with relatively lower temperatures. Low rates of SOM mineralisation, strong leaching, and eluviation give rise to humic topsoil and mostly acid soils with low base saturation like Andosols. Intermediary weathered Humic Andosols are dominant in the forested humid upper slopes (Muchena & Gachene, 1988). Humic Nitisols occur in the middle slopes which are characterized by moderate rainfall and temperature. The Humic Nitisols found in most of the sampled farms are typically deep, weathered soils with moderate to high inherent fertility (Jaetzold et al., 2007). The Chromic Luvisols dominate in lower TNC zones (Wawire et al., 2021). The sampling locations were mainly located in the upper and middle slopes of the study area as per the two land use strata *(Figure 13).*

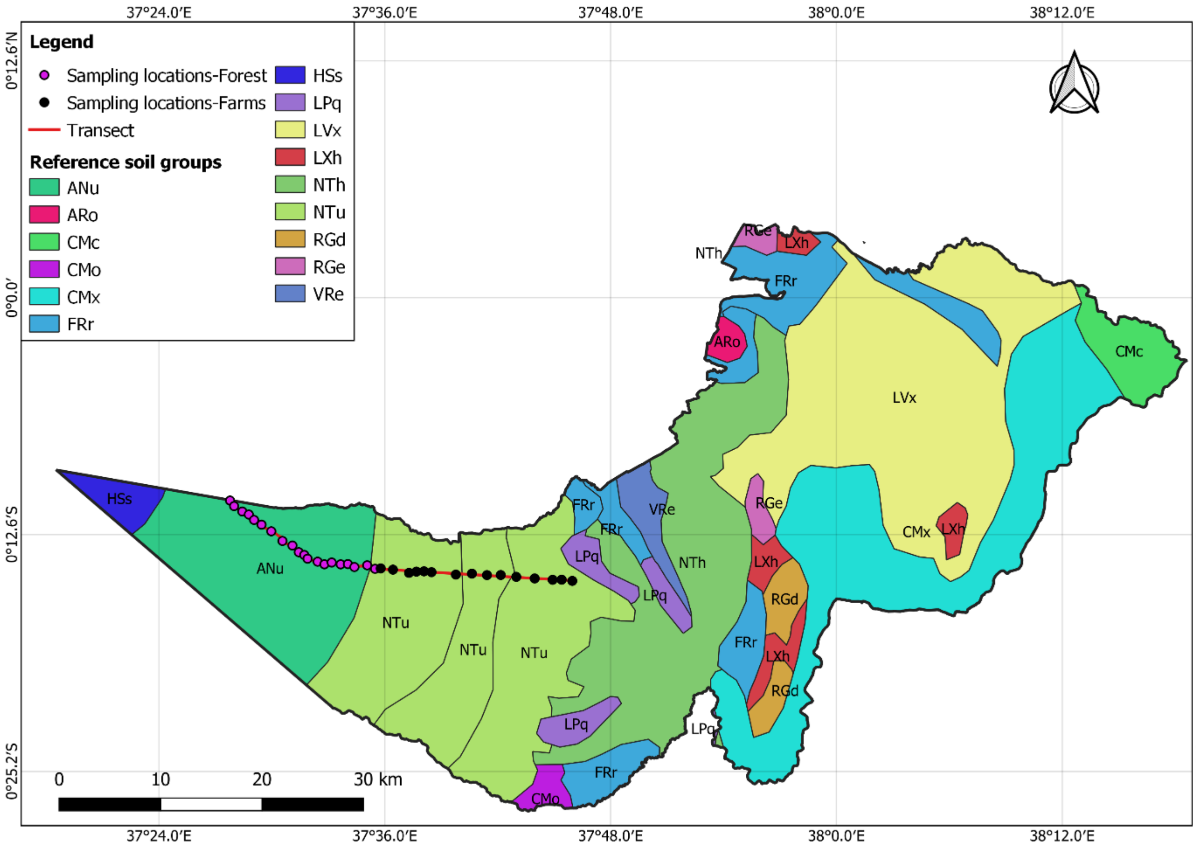

Figure 13: Reference Soil Groups of the study area (Source: author)

Note: ANu = Humic andosols, ARo = Ferralic Arenosols, CMc = Calcaric Cambisols. CMo = Ferralic Cambisols, CMx = Chromic Cambisols, FRr = Rhodic Ferralsols, HSs = Terric Histosols, LPq = Lithic Leptosols, LVx = Chromic Luvisols, LXh = Haplic Lixisols, NTh = Haplic Nitisols, NTu = Humic Nitisols, RGd = Dystric Regosols, RGe = Eutric Regosols, VRe = Eutric Vertisols

3.1.5 Climate

TNC is located between the Upper Midland Zone (UM) and Lower Midland Zone (LM) agroecological zones (AEZs) (Jaetzold et al., 2007). It has a bimodal rainfall pattern with annual precipitation ranging from 500 mm in the lower zones to 2200 mm in the upper zones. Long rains occur from March to June, whereas short rains are experienced from October to December. Temperature ranges from 14 °C in the highlands to 40 °C in the lowlands (County Government of Tharaka Nithi, 2018).

3.1.6 Water Resources

The eastern slopes of the Mt. Kenya ecosystem form a significant water catchment area as it is among the five main water towers of Kenya. TNC is traversed by several rivers, originating from both the Mt. Kenya and Nyambene Hills, and form the tributaries of Tana River which provides water for numerous hydropower stations and domestic users and irrigation schemes (Kenya Wildlife Service, 2010).

3.1.7 Biodiversity

The upper slopes of the study area comprise the Mt. Kenya Forest which has a wide range of flora and fauna. Vegetation in the sampled locations in Mt. Kenya Forest comprises pure bamboo (*Arundinaria alpine*) occurring between 2550 and 2650 m; mixed bamboo with indigenous trees (2450 to 2500 m); indigenous natural forest (1900 to 2400 m) and mixed indigenous natural forest and plantation forest (1700 to 1850 m). Some of the indigenous trees in the forest include the Camphor (*Ocotea usambarensis),* Podo (*Podocarpus latifolius*), Meru Oak (*Vitex Keniensis*), Cedar (*Juniperus procera*), Croton (*Croton macrostachyus*), Wild Olive (*Olea europaea)* and East Africana Rosewood (*Hagenia abyssinica).* Main commercial tree species planted in the plantation zone include Cypress (*Cupressus lusitanica*), Pines (*Casuarina equisetifolia*), and *Eucalyptus spp*. *Grevillea robusta* and *Cupressus lusitanica* are also common in the farms for firewood and timber provision (Kenya Forest Service, 2010).

Animals of conservation interest in the forest include the African elephant (*Loxodonta africana*), leopard (*Panthera pardus*), cape buffalo (*Syncerus caffer caffer)*, Bongo (*Tragelaphus euryceros*), and the black and white colobus monkeys (*Colobus guereza*). Mt. Kenya ecosystem is an Important Bird Area (IBA) as it is home to 53 out of Kenya's 67 African highland biome bird species, including the little-known and threatened Abbott's starling (Kenya Forest Service, 2010; Kenya Wildlife Service, 2010).

3.1.8 Land use land cover

According to the Ministry of Agriculture, Livestock and Fisheries (MoALF), Agriculture is the core land use type in TNC with approximately 59,000 hectares of land in the county under agriculture, of which more than 70% is under food crops, and 20% under cash crops (Ministry of Agriculture Livestock and Fisheries, 2017). About 80% of the county's population is engaged in agricultural activities with both food and cash crops being grown for food, income and livelihoods (Ministry of Agriculture Livestock and Fisheries, 2017). The upper slopes of the study area comprise 36,010 hectares of the Mt. Kenya Forest while bareland in the form of rocks and snow are common at the peak of the mountain (County Government of Tharaka Nithi, 2018). Other LULC types in TNC are grasslands, shrublands, bareland, built-up areas, and water features *(Figure 14).*

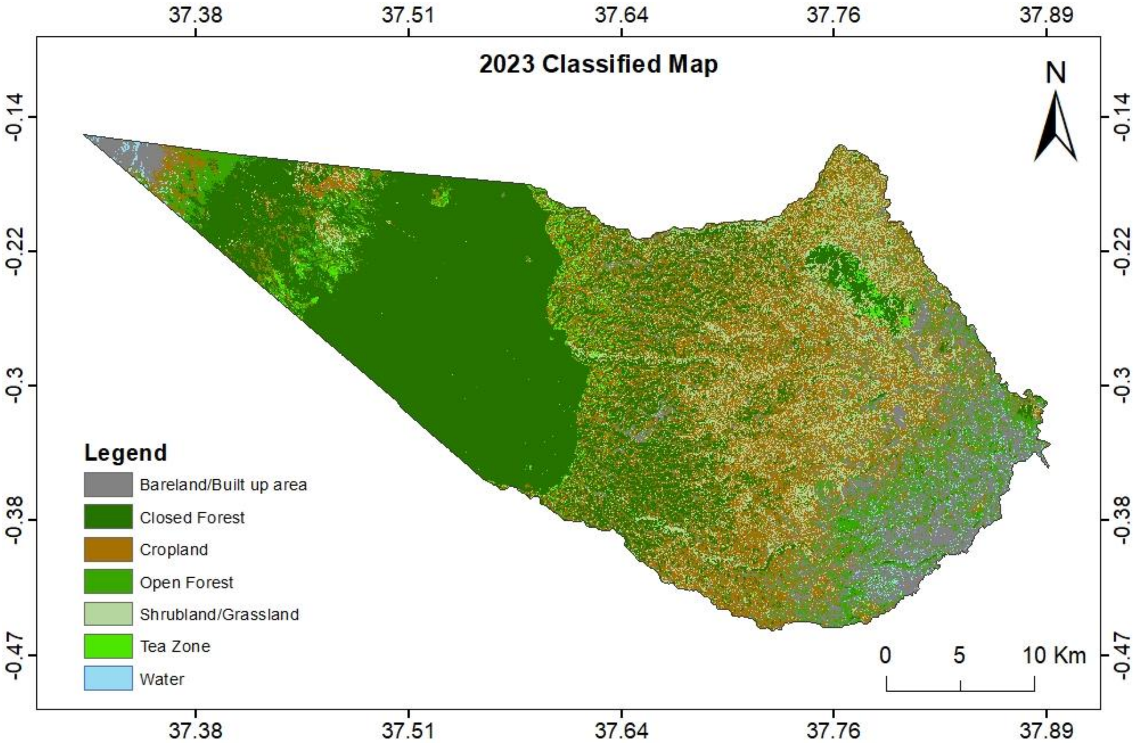

Figure 14: Map showing the LULC types in the study area (Source: author)

3.1.9 Demographic and socio-economic characteristics

TNC has an estimated total population of 393,177 people with a population density estimate of 153 persons per km^2 as per the Kenya Population and Housing Census report of 2019 (Kenya National Bureau of Statistics, 2019). Ethnically, the study area mainly consists of the Chuka, Muthambi, Mwimbi, and Tharaka people of the larger Ameru community (County Government of Tharaka Nithi, 2023; Labeyrie et al., 2014). Rainfed agriculture is the main land use in TNC, with smallholder farmers producing a variety of agricultural products making up the majority of farmers (Wawire et al., 2021). Common food crops include bananas, maize, potatoes, beans, cassava, yams, peas, arrow roots, sweet potatoes, cowpeas, sorghum, and a variety of fruits like mangoes, avocadoes, pawpaw, pineapples, while tea and coffee are the major cash crops (Mairura et al., 2022b). Irrigation is practiced along the river flood plains to grow horticultural crops during dry spells, with the common irrigation methods being furrow, where water is conveyed in open canals, and overhead, where irrigation is done using pipes. Sowing methods include hand-dibbling and drilling, while animals (oxen) are commonly used for ploughing. Livestock keeping is also practiced, with the major livestock being dairy and beef cattle, sheep, goats, and poultry (County Government of Tharaka Nithi, 2023). Forest-adjacent communities rely on the forest for several products and services for their livelihood, including firewood, water, beekeeping, grazing, and medicinal herbs (Kenya Forest Service, 2015). Environmental challenges in the study area include forest fires, human-wildlife conflicts, soil erosion, water pollution from agrochemicals, illegal logging, illegal water abstraction, and improper waste disposal (County Government of Tharaka Nithi, 2018; Kenya Wildlife Service, 2010).

3.2 Soil sampling

3.2.1 Sampling design

A stratified systematic sampling design was adopted for this study. Land use type formed the strata whereby soil samples were systematically collected at 50 m elevation intervals from two land use types: forestland and cropland. This design was purposefully chosen to ensure that the collected soil samples were both representative of the entire study area and provided adequate coverage of the different strata, allowing for a more accurate analysis and interpretation of soil properties in the study area. The study was conducted within a study transect approximately 35 km long and 500 m wide with an elevation range of 1000 to 2650 m. The transect dimensions were selected based on accessibility, safety, and representation of the various altitudes and LULC types. The transect traverses two LULC types: about 18 km of farmland (1000–1700 m) and 17 km of forestland (1700–2650 m). Transect sampling was deliberately chosen to determine the variation of soil properties with elevation and determine the influence of land use and land cover on SOCS. Soils from the forest, considered undisturbed soils, were sampled as a reference since the forest comprises a natural ecosystem, and their results were compared against cultivated soils in the farmlands which is considered disturbed. Samples were collected at two depths (0–20 cm, 20–40 cm) from 34 sampling locations along the transect (19 from the forest and 15 from the farmland).

3.2.2 Soil sampling procedure

The fieldwork was conducted from 25th June 2023 to 10th July 2023. The fieldwork tools and equipment comprised soil augers, soil corers, hoes, shovels, tape measure, plastic zip lock bags, Global Positioning System (GPS), buckets, marker pens, a soil thermometer, a notebook, and a pen. The sampling points along the transect line were pre-determined in Google Earth Pro and mapped in QGIS (3.28.10-Firenze) based on the elevation and land use type. A handheld GPS device (Garmin E Trex 22x, 2.2") was used for navigation to the designated sampling locations in the field and to record the elevation, longitude, and latitudes of the sampling locations. Soil samples were taken within 20 x 20 m sampling locations in 5 x 5 m sampling plots. Vegetation, debris, litter, stones, and roots were first cleared from the sampling plots, after which samples were collected using a soil auger with a 5 cm diameter at two depths of 0–20 cm (topsoil) and 20–40 cm (subsoil). In each sampling plot, the samples were taken at four

(4) sub-locations. One sub-sample was taken at the centre of the plot, and the other three sub-samples were taken in a Y-shaped formation on the circle with a radius of about 2.5 m or three steps from the centre point at equidistance from each other (*Figure 15*).

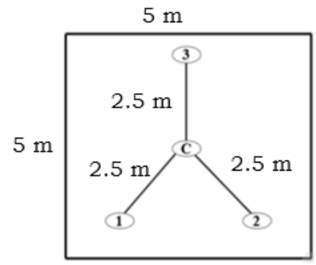

Figure 15: A graphic demonstration of the soil sampling technique used in the study area

The subsamples were then thoroughly mixed to get a composite sample, and soil temperature was recorded using a soil thermometer. About 500 g of the composite sample was collected in each sampling plot for each depth, bagged in plastic bags, and labelled. A portion of the composite sample was then used to test the presence of carbonates in the soil using 1 M hydrochloric acid (HCl). At each sampling location, general site characteristics, including geographical position, elevation, vegetation, and land management practices, were recorded. A total of 68 disturbed samples were collected using an auger (34 locations x 2 soil depths). Additionally, 68 soil core samples from both depths were collected separately using a 100 cm^3 aluminium ring for bulk density determination. Mini pits (~30 cm x 50 cm) were dug to enable coring of the subsoil layer at every sampling point. The core samples were pre-weighed, then oven-dried at 105 °C for 24 hours, and again re-weighed to get the dry weight for bulk density calculation.

3.2.3 Samples preparation and pre-treatment

Preparation of the collected samples was done in Kenya, at the Chuka university soil science laboratory by air-drying, hand removal of roots, and crushing using a mortar and pestle before sieving through a 2 mm sieve. Portions of the soil samples (~200 g) were then packed and shipped to the Hungarian University of Agriculture and Life Sciences (MATE) soil laboratory in Hungary for further physicochemical analysis.

3.2.4 Soil samples analysis

The soil samples for SOC determination were further ground into fine granules using a mortar and pestle. About 5 g of the ground samples were placed in reusable ceramic crucibles before being analysed for total carbon and total nitrogen by dry combustion using the vario MAX cube

CNS elemental analyser. The pH of the soils was measured in the supernatant suspension of soil to a liquid mixture of 1:2.5 ratios. The liquids were distilled water (pH_{H2O}) and 1 M KCl (pH KCl) and measured with a digital pH meter (VWR pHenomenal pH 1100L) after calibrating the instrument with buffer solutions (Búzas, 1988). The distribution of clay, silt, and sand particles (soil texture) was determined by laser diffraction method (LDM) using a laser diffractometer, Mastersizer 3000 (Malvern Instruments, Malvern, UK) using the procedure described by (Makó et al., 2017).

3.2.5 Bulk density and SOCS calculations

The soil BD was calculated as per equation (2)

SOCS (Mg ha^{-1}) for each depth was then estimated using equation (4) (Mishra et al., 2020).

$$SOCS = BD * SOC\% * D \tag{4}$$

Where SOCS = Soil organic carbon stocks (Mg ha^{-1}); BD = Bulk density (g cm^{-3}); SOC% = SOC concentration; D = Sampled soil layer depth (cm).

3.2.6 Statistical analysis of soil data

3.2.6.1 Data preparation and normality test

Field and laboratory data were compiled, cleaned and arranged in Microsoft Office Excel sheets before they were imported to R in readiness for analysis (R Core Team, 2022). A preliminary test for normality among groups was performed on the dataset using the Shapiro-Wilk test before selecting the most suitable statistical analysis.

3.2.6.2 Influence of land use and soil depth on SOCS

After confirming normality of the data ($p > 0.05$), a two-way Analysis of Variance (ANOVA) interaction model was used to test for significant influence of land use, soil depth and their interactions (land use x soil depth) on SOCS in R environment as shown in equation (5). This particular model was selected because it tests whether the effect of one factor (land use) on SOCS depends on the level of the other factor (soil depth).

```
anova_model1 <- aov(SOCS ~ LAND_USE * DEPTH, data = SOIL)    (5)
```

3.2.6.3 Influence of elevation gradient and soil depth on SOCS

Similarly, the effects of elevation gradient, soil depth, and their interaction was tested using a two-way interaction ANOVA model as shown in equation (6).

```
anova_model2 <- aov(SOCS ~ ELEVATION_GRADIENT * DEPTH, data = SOIL)    (6)
```

3.2.6.4 Influence of management practices on SOCS

An additional Excel file, combining the social data and soil data from the sampled households was prepared to enable the analysis of the influence of RSMPs on SOCS in the sampled farms as per objective 4. The file was then imported into R environment after which the additive ANOVA model was used to assess the influence of the categorical RSMPs on SOCS as per equation (7).

anova_model3 <- aov(SOCS ~ Terraces + Agroforestry + Manure…, data = FARM) (7)

Where *anova_model3* = ANOVA model, *SOCS* = Soil organic carbon stock, *FARM* = data

From the analysis, RSMPs with significant impacts on SOCS were identified and further discussed.

3.2.6.4 Mean separation, mean differences and correlation among soil properties

The Tukey's Honestly Significant Difference (HSD) post hoc test was subsequently employed for mean separation in the case of significant differences among the means of the various soil properties. Pairwise comparison tests (t-test) were also used to assess the mean difference between the two land use types and the two depth levels for the different soil properties. The Pearson correlation coefficient was utilised to analyse relationships among soil properties in the forestland and farmland. All analyses were performed at a 95% confidence level using R software version 4.2.2 (R Core Team, 2022) and Microsoft Office Excel 2016.

3.3 Household surveys

In addition, social data was gathered using a questionnaire with closed and open-ended questions from farming households in the study area (Babbie, 2020). This was done in order to characterise the various RSMPs in the study area, gain insights on farmers' SOC and SOM knowledge, assess the determinants of RSMPs adoption, and find out the challenges facing the adoption of RSMPs among the farmers in the Mount Kenya east region.

3.3.1 Target population, and sample size

About 3,798 active smallholder farmers from three administrative wards in the study area (Chogoria, Ganga, Mwimbi) spread across different Agro Ecological Zones (AEZs) formed the target population (*Table 3*). This number of smallholder farmers was obtained from the local administrative officers' records, after which a sample size of 150 households (HHs) was calculated using equation (8) (Israel, 1992).

$$n = \frac{N}{1+N(e^2)} \tag{8}$$

Where: n = sample size, N = Target population size, e = Level of precision (8%)

Therefore,

$$n = \frac{3{,}798}{1 + 3{,}798(0.08^2)}$$

$$n = 150.19 \approx 150$$

Proportionate sampling was used to distribute the number of respondents in each ward as guided by the respective number of farming HHs per ward (*A4*), to enable equal representation *(Table 3)*. Systematic sampling was employed in data collection, where the sampling interval size (k) was arrived at by dividing the total number of farming HHs (N) in each ward by the sample size (n) of the respective ward. Out of the 150 farmers interviewed, 15 were owners of the lands from which the soil samples were collected.

Table 3: Sample size distribution and sampling intervals in the study area

Ward	**Land Area (km^2)**	**AEZs**	**Farming HHs (N)**	**Sample size (n)**	**Percentage (%)**	**Sampling interval (k)**
Chogoria	58.5	UM	1596	63	42	11
Ganga	35.2	UM/LM	1139	45	30	8
Mwimbi	88.1	LM	1063	42	28	7
Total	**181.8**		**3798**	**150**	**100**	

Note: AEZs= Agro Ecological Zones, UM= Upper Midland, LM= Lower Midland

3.3.2 Ethical clearance, research license and consent

Ethical clearance to conduct this study was obtained from the ethics committee of the Doctoral School of Environmental Sciences of the Hungarian University of Agriculture and Life Sciences (MATE), Hungary. A research license was also obtained from The National Commission for Science, Technology, and Innovation (NACOSTI) Kenya and shared with the local administration to facilitate the research. Additionally, verbal consent was obtained from HH heads before commencing the surveys.

3.3.3 Data sources and data collection tools

The fieldwork was conducted from 25th June 2023 to 10th July 2023. HH questionnaire, field observations, and Key Informants Interviews (KII) were used for primary data collection. A cross-sectional HH survey was used to collect data from the farmers using questionnaire with open and close ended questions (*A2)*. The questions were developed in Open Data Kit (ODK), a digitized data collection interface (https://www.getodk.org), after which they were pre-tested on 15 farmers in the neighbouring Mitheru ward and adjusted accordingly. ODK Collect is a free and open-source Android application with the ability to collect data offline (Hartung et al., 2010). Users can download the developed questionnaire forms from the online platform to their android devices, collect data in areas with no internet connectivity, and then upload the data later when a connection is available (Hartung et al., 2010). The questionnaire was administered to the farmers by three trained research assistants from each of the wards of the study area under close supervision. The questions primarily focused on HH socio-economic characteristics (age, education, income, gender, marital status) farm characteristics (size, farm distance from homestead, tenure), institutional factors (access to extension services, access to credit), types of RSMPs (agronomic, physical, vegetative) and farmers' SOM knowledge. In-depth interviews were also conducted with 6 key informants including 3 agricultural extension officers, 2 County government officials and 1 Community Based Organization (CBO) officer working with farmers in the study area. The interviews were conducted face to face lasting from between 30 minutes and one hour and interview information registered using a notebook and a pen (Mugenda & Mugenda, 2003). The interview questions (*A3*) focused on types of RSMPs, RSMPs adoption and challenges facing RSMPs adoption in the study area. Consent was first sought verbally from the interviewees before starting the interviews. Field observations were made at the farm level during the HH surveys on the farming practices and crops grown (Babbie, 2020). The observations were captured using a camera and registered using a notebook and a pen. The interviews and observations were conducted to capture information that might have been overlooked in the HH questionnaire and simultaneously enrich information gathered through HH surveys (Mugenda & Mugenda, 2003).

3.3.4 Statistical analysis of household, observation and interview data

Data gathered from the HH questionnaire was downloaded from the ONA online platform and analysed using Microsoft Office Excel 2016 and STATA version 18 software. Farmers' demographic and socio-economic characteristics, adoption and challenges of RSMPs and SOM knowledge and perceptions were analysed using descriptive and inferential statistics at a 95% probability level. The analysis results were presented in the form of frequency counts, percentage tables, and graphs.

The data from the KIIs were first coded, before being categorised based on the key themes (Babbie, 2020). The themes were analysed based on context and interpreted to establish their relationship with the research questions and study objectives. Triangulation of the observation results was done by cross-referencing with the HH surveys and interview data for validation (Mugenda & Mugenda, 2003).

The binary logistic regression model was then used to explore the influence of demographic, farm, socio-economic, institutional, and bio-physical factors in the adoption of RSMPs using a dichotomous dependent variable (adopters and non-adopters). Adoption and non-adoption of RSMPs were captured at the farm level to provide a holistic view of the RSMPs on the entire farm and to understand the integrated impact of multiple practices across different plots within the farm. This study adopted the logit model given the binary nature of the adoption outcome and the flexibility of the logit model in handling various statistical considerations (Agresti, 2007; Jari & Fraser, 2009). Additionally, the outcome variables used (RSMPs adoption) were dichotomous in nature. It also provides a flexible and interpretable framework for analysing the complex relationships between various factors and the likelihood of RSMPs adoption (Agresti, 2007; Jari & Fraser, 2009). Because the outcome variable is categorical in this case, let $Y = (Y_1, \ldots, Y_k)$ be the vector of k that denotes outcome numbers of n trials of randomized k outcomes. The probability of each outcome's success is denoted by π_i. Therefore, for independent N observations, the multinomial probability that n_1 falls in the first category and π_k falls in k^{th} category, whereby $\sum_{i=1}^{n} \mathrm{y}_j = n$. Thus, the probability function can be stated as shown in equation (9).

$$(y_1, \ldots, y_k, n, \pi_k\ ) = P(Y_1 = y_1, \ldots, Y_k = y_k) = \left(\frac{n!}{y_1!, \ldots, y_k!}\right) \pi_k{}^{y_1} \ldots \pi_k{}^{y_k} \tag{9}$$

The binary logistic regression model utilizes maximum likelihood estimation to evaluate the probability of each categorical membership and is applicable when there is no natural order among categorical responses (Agresti, 2007). According to Tabachnick et al. (2013), the binary logistic regression model is useful in analysing a mix of explanatory variables such as continuous, dichotomous, and discrete variables, as it is in the case of this study *(Table 4)*. For instance, considering the first category as the reference, the logistic of the other categories is expressed as shown in equation (10).

$$Logit\ (\ \pi_i) = \ln\left(\frac{\pi_i}{\pi_1}\right) = x_i^T \upbeta_i \mathrm{i} = 1, \ldots, M \tag{10}$$

where $(M-1)$ logistic equations are utilized simultaneously in estimating β_j. After calculating $\widehat{\beta_J}$ parameter, the probability of every category is expressed as shown in equation (11).

$$\pi_i = \frac{\exp\left(x_i^T \beta_i\right)}{1 + \sum_{i=2}^{n} \exp\left(x_i^T \widehat{\beta_i}\right)} \; for\ \mathrm{i} = 2, \dots, M \tag{11}$$

where $\widehat{\beta_J}$ is defined as 0 and $\sum \pi_i$=1

Expressing the binary logistic regression model depicting the HH determinants of adopting RSMPs in stochastic form, the model is presented in equation (12).

$$Y_i = \ln\left(\frac{\mathrm{P}\,\pi_i}{1 - \mathrm{P}\,\pi_i}\right) = \beta_0 + \beta_1 X_1 + \beta_1 X_1 + \cdots \beta_k X_k + \beta_d D_d + \mu_i \tag{12}$$

Where Y_i is the binary outcome variable of interest (adoption of RSMPs), $\mathrm{P}\,\pi_i$ is the probability of adopting RSMPs and $1 - \mathrm{P}\,\pi_i$, is the probability of not adopting RSMPs, β_0 denotes the intercept, $\beta_1, \dots, \beta_k$ denotes the coefficient estimates of the independent variables (HH factors), β_d is the coefficient estimate of the dummy variable for the ward arable fixed effect denoted by D, and the error term is denoted by μ_i. The subscript i denotes HHs $i = 1, \dots, 150$. In this case, the adoption of RSMPs is the outcome variable taking value 1 if the HH is an adopter and 0 if the HH is a non-adopter. Various HH factors such as age, gender, marital status, education level, family size, farm size, access to extension services, access to credit, labour type, and average monthly income (on and off-farm) were included as the explanatory variables of the RSMPs adoption. After determining the effect of each explanatory variable on the binary response variable, marginal effect which is used to determine the effect of the independent variables per every unit change on the response variable was applied while holding every other parameter constant (Degfe et al., 2023). Computation of the marginal effects is ideal for the binary logistic regression model since the estimated coefficient estimates do not depict the magnitude of effects of the explanatory variables on the categories of the dichotomous outcome variable. In the logistic model, the slope coefficient of each variable provides the change in the log of odds linked to the unit change in the variable while holding other variables constant. The binary logistic model assumes that the log of odd ratios is linearly related to Xi. Thus, the marginal effects of changes in the independent variables are shown in equation (13).

$$\pi_i = \frac{\partial \Pr(Y = 1/X)}{\partial \mathrm{X}} = \beta_i \mathrm{X}_i (1 - P_i) \tag{13}$$

This signifies the rate of change in the probability of an event occurring, where β_i is the partial regression coefficient for the i^{th} regressor.

A correlation analysis was conducted to determine the degree of association between the household covariates and the adoption of RSMPs (Miles, 2014; Studenmund, 2014). This was necessary in pointing out the magnitude of the association as a way of ascertaining the likelihood of the presence of multicollinearity (Daoud, 2018). All the hypothesized exogenous variables were checked for the probable presence of multicollinearity before running the binary logistic regression model since there could be cases of recall bias in the HH responses. A requisite threshold correlation coefficient of less than 0.8, implies the absence of multicollinearity issues (Daoud, 2018).

A Variance Inflation Factor (VIF) analysis was also conducted in STATA (version 18) to assess multicollinearity among the explanatory variables (Gujarati, 2003). Before running the VIF test, both numerical and categorical variables underwent preprocessing. For the numerical variables, outliers were identified and addressed to prevent them from distorting relationships within the model. These variables were also tested for linearity and normality to ensure they met the assumptions necessary for regression analysis (Kutner et al., 2004). On the other hand, the categorical variables were transformed into binary (dummy) variables, where each category was represented as either 1 or 0, with one category serving as the reference group. This approach helped avoid the dummy variable trap, which occurs when all categories are included, resulting in perfect collinearity among the dummy variables (O'Brien, 2007).

The VIF analysis measures how much the variance of a regression coefficient is inflated due to collinearity with other predictors. A VIF value exceeding 5 and tolerance values less than 0.1, is commonly taken as an indication of high multicollinearity, which can lead to unstable regression coefficients (Gujarati, 2003). For the numerical variables, VIF measures how much the standard error of each continuous predictor is inflated by its correlation with other continuous variables. For the categorical variables, after conversion into dummy variables, VIF is calculated for each dummy variable individually. This allows for detection of any collinearity between the dummy variables and the other predictors, whether categorical or continuous (Gujarati, 2003; Kutner et al., 2004).

The VIF test is applicable to both numerical and categorical variables (O'Brien, 2007). For continuous variables, it detects multicollinearity among the continuous predictors, while for categorical variables, the test evaluates each dummy variable for potential collinearity with other variables in the model (O'Brien, 2007). The VIF analysis ensured that any multicollinearity in the model was identified and addressed, leading to more reliable and interpretable results (Miles, 2014; Studenmund, 2014). A summary of the study variables is presented in *(Table 4)*.

Table 4: Table showing the description of the study variables

Variable name	**Variable type**	**Variable Description**	**Measurement**	**Expected Sign**
		Dependent Variable		
Adoption	Binary	Farmers' adoption of RSMPs	Dummy (adopters=1, non-adopters=0)	
		Independent Variables		
Age	Continuous	Age of household head	Years	+/-
Household size	Discrete	No. of family members	Whole numbers (1, 2...)	+
Farm size	Continuous	Household farm size	Acres	+/-
Distance	Continuous	Distance from homestead to farm	Meters	-
Gender	Categorical	Household head sex	Dummy (female=0, male=1)	+
Marital status	Categorical	Household head marital status	Dummy (unmarried=0, married=1)	-
Education	Categorical	Household head's education	Dummy (no formal=0, formal=1)	+/-
Income	Categorical	Household average monthly income (KES)	Dummy (<5000=0, >5000=1)	+/-
Credit	Categorical	Household access to credit	Dummy (no=0, yes=1)	+
Labour type	Categorical	Household labour type	Dummy (family=0, hired=1)	+
Extension services	Categorical	Household access to extension services	Dummy (no=0, yes=1)	+

* *KES = Kenya shillings*

4. RESULTS AND DISCUSSION

This chapter is arranged into different sub-sections based on the study objectives. It encompasses results and discussions on soil physicochemical properties in the farmland and forestland and their relationships, the variations of SOCS along the elevation gradients, types of RSMPs carried out in the study area, farmers' adoption and challenges in adopting RSMPs, influence of RSMPs on SOCS and farmers' knowledge and perceived benefits of SOM.

4.1 Soil properties under different land use types and soil depths

4.1.1 Physical and chemical characteristics of the study area soils

The analysis of the study area's soils physicochemical characteristics and their relationships was carried out using ANOVA, Tukey's HSD tests, and t-tests in R (R Core Team, 2022). A summary of the descriptive statistics of select soil physical characteristics (BD, soil texture, soil temperature, sand, silt, and clay) and chemical characteristics (SOC, pH, TN) from the field measurements and the analysed samples for the two land use types and soil depths are presented in *Table 5*.

Table 5: Summary of select soil physicochemical properties under the two land use types on the eastern slopes of Mount Kenya

Soil property	**Soil depth (cm)**	**Land use type**					
		Forestland			**Farmland**		
		min	**max**	**(mean ± SD)**	**min**	**max**	**(mean ± SD)**
BD	0–20	0.44	0.78	0.60 ± 0.11bB	0.66	0.99	0.85 ± 0.11aA
(g cm^{-3})	20–40	0.49	0.81	0.68 ± 0.11bA	0.75	1.11	0.92 ± 0.11aA
	0–40			0.64 ± 0.11b			0.88 ± 0.12a
pH	0–20	3.70	5.70	4.45 ± 0.54bA	4.70	5.90	5.50 ± 0.37aA
	20–40	3.80	6.00	4.55 ± 0.55bA	4.50	6.00	5.50 ± 0.46aA
	0–40			4.50 ± 0.54b			5.50 ± 0.41a
SOC (%)	0–20	5.67	17.43	10.92 ± 3.88aA	1.23	3.77	2.36 ± 0.72bA
	20–40	2.70	14.02	7.57 ± 3.37aB	0.89	3.16	1.86 ± 0.71bA
	0–40			9.24 ± 3.96a			2.11 ± 0.75b
TN (%)	0–20	0.43	1.54	0.89 ± 0.32aA	0.14	0.30	0.22 ± 0.05bA
	20–40	0.23	1.12	0.60 ± 0.26aB	0.11	0.27	0.17 ± 0.05bB
	0–40			0.75 ± 0.32a			0.19 ± 0.05b
Soil Temp.	0–20	14	17	15.58 ± 0.90bA	18	27	24 ± 2.59aA
(°C)	20–40	13	17	15.13 ± 1.13bA	17	26	22.50 ± 2.67aA
	0–40			15.35 ± 1.03b			23.25 ± 2.69a
Sand (%)	0–20	17.55	85.33	39.45 ± 18.61aA	9.85	36.68	19.87 ± 8.30bA
	20–40	5.45	65.51	23.94 ± 17.90aB	6.47	19.43	12.48 ± 3.44bB
	0–40			31.69 ± 19.65a			16.18 ± 7.29b
Silt (%)	0–20	13.03	57.58	47.82 ± 12.83aA	31.16	59.47	43.40 ± 7.09aA
	20–40	30.07	61.98	53.08 ± 8.33aA	38.94	52.35	44.26 ± 3.99bA
	0–40			50.45 ± 10.99a			43.83 ± 5.67b
Clay (%)	0–20	1.64	24.86	12.73 ± 6.78bB	30.13	45.67	36.73 ± 4.43aB
	20–40	4.42	37.31	22.98 ± 11.62bA	34.69	54.57	43.26 ± 5.33aA
	0–40			17.86 ± 10.73b			39.99 ± 5.85a
Texture	0–20			Loam			Silty Clay Loam
	20–40			Silt Loam			Silty Clay
	0–40			Silt Loam			Silty Clay Loam

Note: Different lowercase letters within a row indicate a significant difference for each soil property between land use types. Within a column, different uppercase letters indicate a significant difference between soil depths for each property.

The studied soils displayed some variations in their physical and chemical properties based on the land use types and the soil depths. The physical and chemical properties of soil vary in response to environmental and anthropogenic driving factors (Soucémarianadin et al., 2018; Stockmann et al., 2013). The mean BD of the farmland soil (0.88 ± 0.12 g cm^{-3}) was significantly higher (p<0.001) than the forestland soil (0.64 ± 0.11 g cm^{-3}). BD was significantly different ($p < 0.05$) between the forestland's topsoil and subsoil, with lower values recorded in the topsoil. There were no significant differences ($p > 0.05$) in BD across the two depths in the farmland. These results are in line with findings from other studies under similar landscapes (Geremew et al., 2023; Tadese et al., 2023; Toru & Kibret, 2019). The low BD values in the forestland can be attributed to higher and continuous SOM inputs from the forest vegetation and lesser human disturbances when compared to the farmland. Higher BD values were observed in farmland due to less SOM content, higher soil compaction from farming practices like tillage and livestock trampling in the case of mixed farming (Ghimire et al., 2023; Toru & Kibret, 2019). The increase in BD with incremental soil depth could also be related to the decreased SOM content and the compaction pressure of the overlying soil horizons (Ghimire et al., 2023). Other researchers have likewise reported that surface soil layers generally have high SOM content, better particle size distribution, good aggregation, and root penetration, hence the low BD values (Amanuel et al., 2018; Muktar et al., 2018). Soils in the farms had BD ranging from 0.66 to 1.11 g $cm^{-3,}$ which is within the range classified as good for agricultural productivity (Buraka et al., 2022). These values were, however, low compared to most mineral soils, which have a BD ranging between 1.0 g cm^{-3} and 1.5 g cm^{-3} (Tarus & Nadir, 2020) due to differences in soil types, specifically the silt and clay content.

Soil pH in the two land uses was generally acidic as they ranged from 3.7 to 6.0. The forest soils were very strongly acidic (4.50 ± 0.54), while the farm soils were strongly acidic (5.50 ± 0.41). Soil pH exhibited significant ($p < 0.05$) variation between land uses but not within soil depths in the individual land use types. Soils developed from non-calcareous parent materials, which is typical of the study area, are inherently acidic (Kanyanjua et al., 2002). The varying pH values between the two land use types can be linked to differences in vegetation density and composition, soil moisture, and temperature. Soils naturally become acidic in humid regions due to the leaching of basic cations under high precipitation conditions (Kanyanjua et al., 2002). Higher mean annual rainfall amounts are received in the forestland than in the farmland. This is due to the dense vegetation and a layered canopy structure of the forest which helps enhance local humidity through transpiration and interception of rainfall. This contributes to higher moisture content in the forest atmosphere, promoting cloud formation and more localized rainfall (County Government of Tharaka Nithi, 2018). Lower pH in the forest might also be associated with the breakdown of SOM on the forest floor by soil microbes. This process leads to the formation of carbonic acid (H_2CO_3) from the reaction of CO_2 produced by the microbial decomposition of SOM and root respiration and H_2O from precipitation (Kumar et al., 2018). Terrestrial ecosystems which are characterised by high rainfall amounts, low temperatures, and less disturbances and dense vegetation cover are likely to have lower pH values when compared to disturbed ecosystems with less vegetation cover and lower precipitation amounts (Adams et al., 2019; Kumar et al., 2018; Logan & Floate, 1985). Acidic soils also dominated the farmlands. In Kenya, acidic soils cover about 13% (7.5 million hectares) of the total agricultural land and contribute significantly to the economy through cash crop and dairy production (Kanyanjua et al., 2002). Several agricultural enterprises in Kenya, including tea, coffee, pyrethrum, potatoes, pineapples, passion fruits, and bananas, are well adapted to acidic conditions (Kanyanjua et al., 2002). These enterprises contribute significantly to Kenya's economy by providing food, employment, and export revenue.

Soil temperature was significantly lower ($p<0.001$) in the forestland (15.35 ± 1.03°C) than in the farmland (23.25 ± 2.69°C). This is due to the vegetation cover in the forest which prevents direct sunlight to the soil. Similarly, significantly high TN content occurred in forest soils (0.75 ± 0.32%) compared to farm soils (0.19 ± 0.05%). The high TN level in the forestland is linked to high forest SOC, which is the major source of TN (Landon, 2014). The TN content showed a decreasing trend with increasing soil depth in both land use types.

As for the soil texture, forestland soils comprised silt loam in the subsoil and the aggregated depth, while the topsoil was primarily loam. In the farmland, silty clay loam was dominant in the topsoil, while silty clay occurred in the subsoil *(Table 5)*. Except for the silt in the topsoil layer, the sand, silt, and clay fractions differed significantly at all corresponding depths between the two land use types. Higher sand and silt content were measured across the two depths in the forestland. On the contrary, significantly higher clay content was recorded at both depths in the farmland *(Table 5)*. Sand content exhibited a downward trend with depth for both land use types, while clay and silt, on the other hand, showed an upward trend with soil depth in both land use types. Humic Andosols dominate the forestland, hence the observed high sand content, while Humic Nitisols are prevalent in the farms, thus the high clay content in the farmland (Mairura et al., 2022a; Muchena & Gachene, 1988). The dominance of the Humic Andosols in the forest is due to its volcanic ash origin, high rainfall, lower temperatures, and abundant organic matter from forest vegetation, leading to the slow decomposition of humus while Humic Nitisols, found in farmlands, are influenced by basalt origin, moderate rainfall and continuous cultivation where farming practices like manure application enhance organic content and structure suitable for crop production (IUSS Working Group WRB, 2015; Muchena & Gachene, 1988; Wawire et al., 2021). Similar findings were recorded in the Birr watershed, upper Blue Nile River Basin, Ethiopia, where sand fractions were higher in natural and mixed forestland while cropland had higher clay fractions (Amanuel et al., 2018). The higher clay content in the subsoil for both land use types can be attributed to downward translocation.

4.1.2 SOC concentrations and stocks under different land uses

The ANOVA model results showed land use had a very highly significant effect on SOC and SOCS ($p<0.001$), soil depth had a highly significant effect on SOC and SOCS ($p<0.01$), while their interaction (land use x soil depth) also had a significant effect ($p<0.05$) on SOC and SOCS in the Mount Kenya east region *(Table 6)*. The Tukey HSD test further revealed significant mean differences in SOC and SOCS between the two land use types and soil depths.

Table 6: Two-way ANOVA results showing the effect of land use, soil depth and their interaction on SOC and SOCS on the eastern slopes of Mount Kenya.

		SOC			
	Df	**Sum Square**	**F value**	**P-value**	**Significance**
Land use	1	853.2	111.65	<0.001	***
Soil depth	1	74.3	9.72	0.0027	**
Land use x Soil depth	1	33.7	4.41	0.0396	*
Residuals	64	489.1			
		SOCS			
	Df	**Sum Square**	**F value**	**P-value**	**Significance**
Land use	1	94522	204.02	<0.001	***
Soil depth	1	5402	11.66	0.0011	**
Land use x Soil depth	1	1979	4.27	0.0428	*
Residuals	64	29651			

*Note: *, **, *** indicates significance at $p < 0.05$, $p<0.01$, and $p<0.001$ respectively.*

All measured Total Carbon was considered as SOC based on the low pH values (<7.0) recorded, negative HCl test in the field, and confirmed absence or insignificant amounts of carbonates in the study area soils from previous studies (Batjes, 2004; Segnini et al., 2019). The highest SOC content (17.43%) was present in the forestland, while the lowest SOC (0.89%) was recorded in farmland *(Table 5)*. SOC was significantly higher in the forestland than in the farmland for both depths (*Figure 16*).

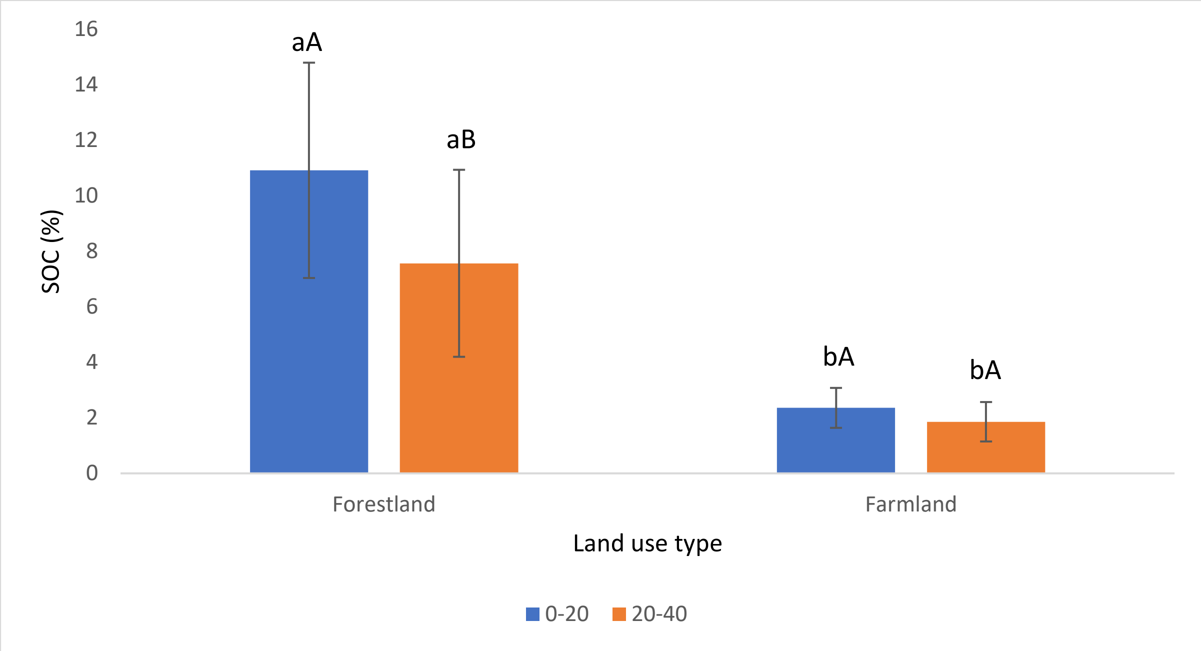

Figure 16: SOC at 0–20 and 20–40 cm depths by land use type in the study sites

Note: Different lower cases indicate significant differences in SOC between land use types within the same soil depths, whereas different upper cases indicate significant differences in SOC between soil depths within the same land use type.

The high SOC in the forestland can be credited to higher and continuous SOM inputs from the forest vegetation litter, and the decomposition of plant roots. In addition, forests have a superior biomass production rate from the diverse vegetation types, resulting in the regular addition of litter to the soils (Shrama et al., 2023). Moreover, forest soils were predominantly Humic Andosols, which characteristically contain the highest SOC content among the Kenyan soils when compared with the Humic Nitisols, which dominate the farmlands of the study area (Batjes, 2004; Muchena & Gachene, 1988). On the other hand, soils in the farmland have lower SOM inputs, are less protected, and are more disturbed compared to the forest soils. Previous research has shown that SOC from the surface to about 20 cm soil depth is prone to frequent perturbations due to the nature of smallholder agricultural practices in Kenya (Njeru et al., 2017). Low levels of SOC in the farmland can be ascribed to continuous cultivation, which enables hastened SOM decomposition. It has been established that tillage physically disrupts soil aggregates, thereby exposing SOM to microbes for decomposition, resulting in SOC mineralization and subsequent release of CO_2 gas into the atmosphere (Lal, 2004a; Segnini et al., 2011). The farmland soils are also prone to water and wind erosion due to less ground cover and the rugged terrain of the study area. The adoption of SWCPs, which could help reduce erosion, is uneven in TNC despite the established vulnerability of the study area soils to soil erosion (Nganga et al., 2019). Erosion results in SOM loss, which subsequently leads to lower SOCS. Crop residue is among the key sources of SOC in farmlands.

Mean SOCS (Mg ha^{-1}) were calculated for the two soil depths (0–20, 20–40 cm) and combined layer (0–40 cm). The mean SOCS in the 0–20 cm depth of the forestland (124.82 ± 25.78 Mg ha^{-1}) was significantly higher (p<0.001) than in farmland (38.86 ± 8.49 Mg ha^{-1}) (*Figure 17*). A similar trend was observed in the 20–40 cm depth with a higher mean SOCS in forestland (97.41 ± 29.15 Mg ha^{-1}) compared to farmland (33.18 ± 9.95 Mg ha^{-1}). The mean SOCS in the aggregated 0–40 cm depth in the forestland was also significantly higher (p<0.001) at 111.11± 30.49 Mg ha^{-1} compared to the farmland (36.02 ± 9.54 Mg ha^{-1}). There was a notable decrease in SOCS with increased soil depth in both land use types, with a significant difference between the two depths in the forestland *(Figure 17)*.

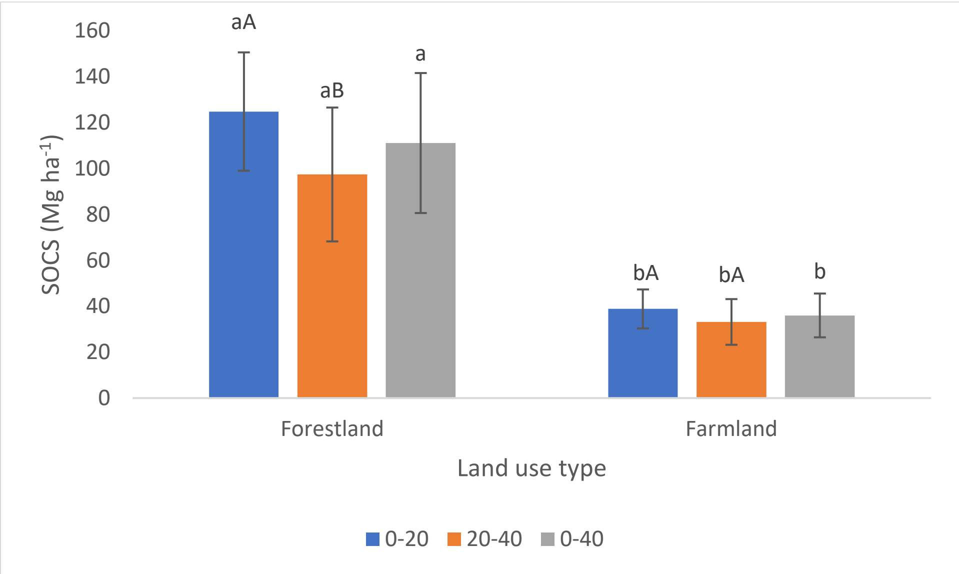

Figure 17: SOCS at 0–20, 20–40, 0–40 cm depths by land use type in the study sites

Note: Different lower cases indicate significant differences in SOCS between land use types within the same soil depths, whereas different upper cases indicate significant differences in SOCS between soil depths within the same land use type.

About a third of the global SOCS is stored in forested areas, underscoring the significant role of forests, especially tropical forests, in carbon sequestration and accumulation (FAO & ITPS, 2020). It is reported that the highest SOCS (>100 Mg ha^{-1}) in the top 30 cm of Kenyan soils are located in the major forest ecosystems, including the Mt Kenya forest (Vågen et al., 2018). The dense vegetation cover in forestland offers a protective cover to the surface soils, thereby reducing SOM loss from wind and water erosion. The lower SOC content and stocks in farmlands can be associated with the removal of crop biomass during harvesting, competing uses of crop residue (as livestock fodder), and burning of crop residue after harvest. Removal of crop residues can have an adverse impact on soil quality by causing the depletion of SOC (Lal, 2007a). An interview with the agricultural extension officers revealed that burning residual biomass is a common land preparation practice in the study area before a new cultivation season. *"As part of land preparation before every new planting season, it is common practice in this region for farmers to burn the crop residual biomass as a way of clearing the land"* stated one of the agricultural extension officers during the interview. Residue burning has been previously reported by other scientists as a method of land preparation in Kenya and elsewhere (Bhuvaneshwari et al., 2019; Segnini et al., 2011; Wawire et al., 2021). Most farmers in the study area also utilise crop residues as livestock feed, as mixed farming is commonly practiced in TNC.

LULC changes is common in montane forest ecosystems and poses a threat to SOC storage as they affect the plant community, net primary productivity, and soil conditions of the affected areas, subsequently altering the SOM quality and quantity (Batjes, 1996; Dorji et al., 2014; Were et al., 2015). Parts of the farmland in the study area, especially near the forest edge, used to be under natural forest cover many decades ago (Bussmann, 2006; Kenya Forest Service, 2010). This was proven by the presence of some remnants of indigenous forest tree species in the farmland, proving that the conversion of the natural forest to farms has contributed to a significant loss of SOC. Soil erosion and land degradation are the likely outcomes of LULC changes, especially when native vegetation is removed and replaced with annual agricultural crops (Dorji et al., 2014). Much of the SOC losses in Kenya have been largely attributed to the rapid expansion of agricultural lands and the conversion of forestlands into croplands (Batjes, 2004; Rotich & Ojwang, 2021; Vågen & Winowiecki, 2013; Were et al., 2015). Similar comparative studies in adjacent land use types of Kenyan montane forest ecosystems have also reported higher SOC and SOCS in forestland compared to farmlands (Njeru et al., 2017; Segnini et al., 2019; Were et al., 2015).

Collectively, SOC and SOCS decreased with the increase of soil depth for both land uses. Most studies globally have established that SOCS are generally higher in surface than sub-surface horizons (Ali et al., 2017; Bangroo et al., 2017; Blackburn et al., 2022). The higher SOC and SOCS in the surface horizons compared to subsurface horizons can be linked to the continuous addition of undecayed and partially decomposed plant and animal remains.

4.1.3 Relationships between SOC and other soil properties

The Pearson correlation coefficient analysis was conducted for a detailed relationship between SOCS and the other soil properties (BD, pH, SOC, TN, soil temperature, sand, silt, and clay) for the two land use types.

4.1.3.1 Correlation between SOCS and other soil properties in the forestland

The analysis revealed SOCS in the forestland had a strong positive correlation with SOC, TN, and sand and a weak positive correlation with pH. Conversely, a strong negative correlation was observed between SOCS, BD, and clay, while a weak negative correlation existed between SOCS, soil temperature, and silt *(Figure 18)*.

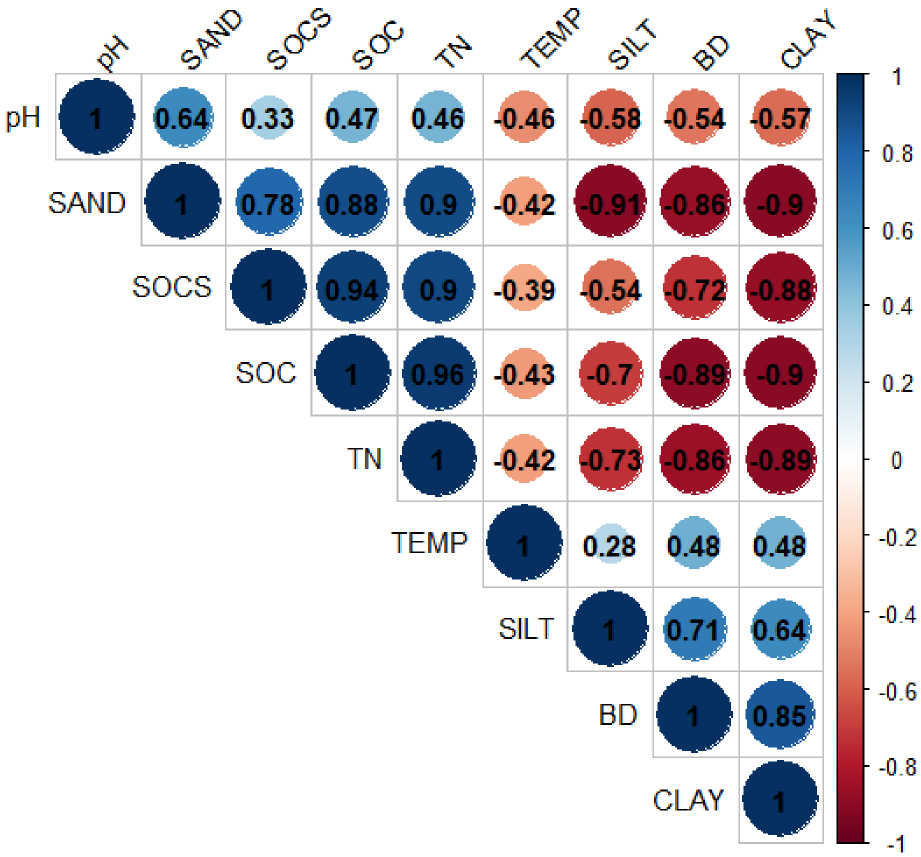

Figure 18: Correlation plot showing the relationship among forestland soil properties

Note$_1$: Positive correlations are shown in blue, negative correlations in red, and the intensity of the colour corresponds to the strength of the correlation.

Note$_2$: SOCS= Soil organic carbon stocks, SOC= Soil organic carbon concentration, TN = Total nitrogen, TEMP = Soil temperature, BD= Bulk density.

4.1.3.2 Correlation between SOCS and other soil properties in the farmland

A strong positive correlation existed in the farmland between SOCS, SOC, and TN. Silt had a strong positive correlation with SOCS. On the other hand, a strong negative correlation was observed between SOCS, BD, and clay, while a weak negative correlation existed between SOCS, soil temperature, and pH *(Figure 19)*.

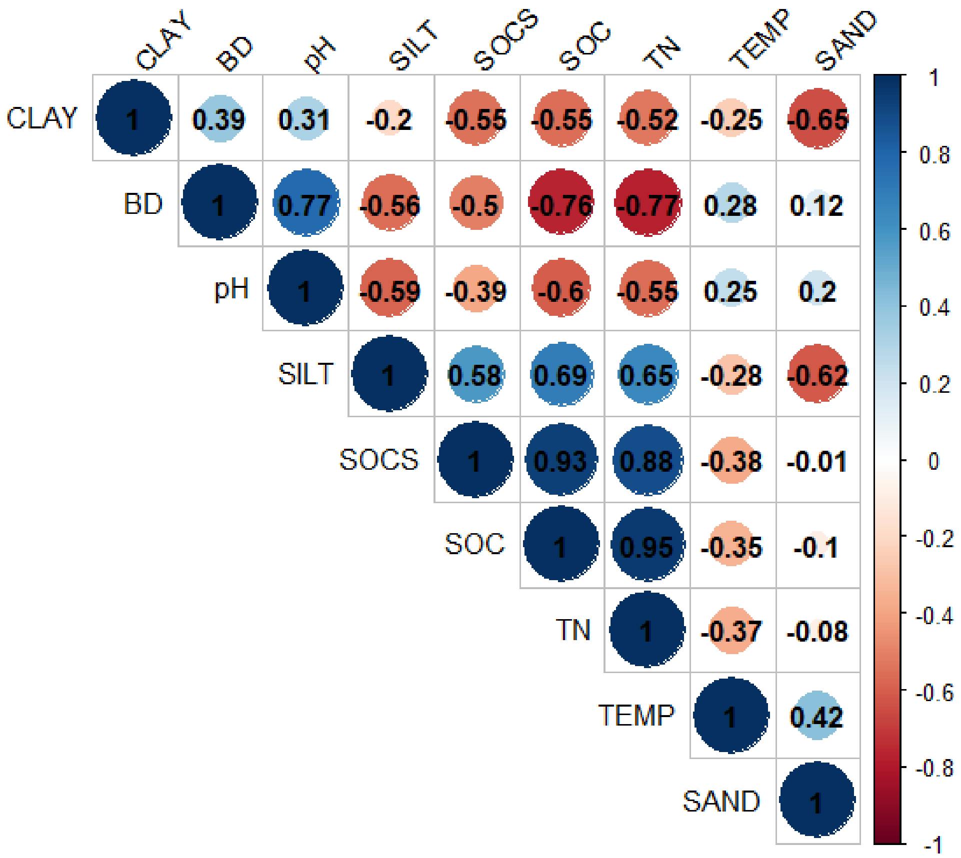

Figure 19: Correlation plot showing the relationship among farmland soil properties

Note₁: Positive correlations are shown in blue, negative correlations in red, and the intensity of the colour corresponds to the strength of the correlation.

Note₂: SOCS= Soil organic carbon stocks, SOC= Soil organic carbon concentration, TN = Total nitrogen, TEMP = Soil temperature, BD= Bulk density

SOCS were negatively correlated with BD for both land use types. Our finding is consistent with previous studies, which also exhibited a negative relationship between SOCS and BD (Ali et al., 2017; Cao et al., 2013; Wang et al., 2018). The inverse relationship between BD and SOCS implies that the lower the SOCS value, the higher the BD value, as SOC has a very low weight per unit volume (Geremew et al., 2023). The negative correlation between soil pH and SOCS in the farmland could be due to H^+ release from SOM, which reduces pH since SOM is one of the main sources of H^+ in soil (Satrio et al., 2009). A negative correlation between SOCS and soil temperature was observed in the study area for both land use types. A steady increase in soil temperature with reduced elevation was evident in the study area. Temperature affects microbial activity and decomposition rates (Bonnett et al., 2006). Lower temperatures result in SOM accumulation because of the slower breakdown of SOM by microorganisms (Gebeyehu et al., 2019). Increasing temperatures down the elevation gradient contribute to increased SOC loss via decomposition, reducing SOCS (Davidson & Janssens, 2006). SOC is the major source of TN, hence the observed positive correlation between SOCS and TN (Landon, 2014).

Contrary to other studies under similar land uses where higher clay contents were associated with higher SOCS (Rumpel & Kögel-Knabner, 2011; Zhong et al., 2018), the results showed a significant negative correlation between SOCS and clay, most notably in the forestland. This observation is largely attributed to the study area's soils, vegetation types and climate. It is an indication that soil physical and chemical characteristics under similar land uses aren't universally consistent but rather contingent upon various factors such as soil type, climatic conditions, vegetation types, and management practices (Adiyah et al., 2022). Similar findings were reported in Mount Bambouto of Central Africa and the Ashanti region of Ghana, where SOCS exhibited a positive significant correlation with sand and a negative significant correlation with clay (Adiyah et al., 2022; Tsozué et al., 2019).

4.2 Variation of soil properties along the elevation gradient

4.2.1 Soil properties within different elevation gradients

The statistical estimates (mean ± SD) of select soil physical and chemical properties based on elevation gradient were calculated and summarised in *Table 7.* The BD ranged from 0.48 ± 0.05 g cm^{-3} in the upper forestland's 0–20 cm depth to 1.03 ± 0.09 g cm^{-3} in the lower farmland's 20–40 cm depth. BD values increased down the elevation gradient for both soil depths *(Table 7)*. The lowest soil pH (4.18 ± 0.22) was found in the lower forestland, most likely due to the presence of *eucalyptus spp.*, while the highest pH (5.78 ± 0.08) was recorded in the lower farmland *(Table 7)*. The leaves and bark of *eucalyptus spp.* produce acidic litter and allelopathic compounds which contributes to a decrease in soil pH over time (Aweto & Moleele, 2005). *Eucalyptus spp.* is also fast-growing and can deplete the soil of base cations (calcium, magnesium, and potassium) that help to buffer soil acidity. This uptake reduces the soil's ability to neutralize acids, leading to acidification (Soumare et al., 2015).

Soil temperatures showed a steadily increasing trend from the highest elevation gradient (14.67 ± 0.49 °C) to the lowest elevation (25.15 ± 1.33 °C). Previous studies have similarly reported an increase in soil temperature down the elevation gradient, which in turn leads to increased rates of SOM decomposition, thereby causing the depletion of SOC (Choudhury et al., 2016; Phillips et al., 2019). The TN content generally increased with increasing elevation gradient due to its established positive correlation with SOC *(Table 7)*. The increase in TN with elevation can be largely attributed to the co-accumulation of nitrogen with SOC, as both are products of OM decomposition. The slow turnover of OM, combined with higher biomass production, is the key driver of this relationship (Ziviani et al., 2024). These findings are supported by various studies across different ecosystems that show a similar positive correlation between SOC and TN with increasing elevation (Okello et al., 2022; Tarus & Nadir, 2020; Zhang et al., 2021).

The mean sand contents for the aggregated depth ranged from a low of 12.54 ± 2.23% in the upper farmland to 52.64 ± 17.82% in the upper forestland, which was predominantly under bamboo (*Arundinaria alpine)* coverage hence the coarse texture. Higher sand content was noted in the 0–20 cm than in the 20–40 cm depth, most notably in the higher elevation gradients *(Table 7).* Silt content showed less variation with elevation gradient, ranging between 40.38 ± 3.59% and 55.71 ± 2.32%. Clay content ranged from a minimum of 6.56 ± 3.19% in the upper forestland to a maximum of 41.46 ± 6.91% in the middle farmland, increasing from the upper part of the soils (0–20 cm) to the bottom (20–40 cm) at each elevation gradient. This observation can be linked to the translocation of clay into deeper layers due to the high precipitation received, especially in the higher elevation gradients (Dorji et al., 2014). Soil texture ranged from clay loam (lower farmland), silty clay (middle farmland), silty clay loam (upper farmland), clay loam (lower and middle forestland), and sandy loam (upper forestland) *(Table 7)*.

Table 7: Select soil physicochemical properties along the elevation gradient (mean ± SD) on the eastern slopes of Mount Kenya.

Soil properties	**Soil depth (cm)**	**Elevation gradient (m)**					
		1000–1200	**1200–1450**	**1450–1700**	**1700–2000**	**2000–2350**	**2350–2650**
BD (g cm^{-3})	0–20	0.95 ± 0.04	0.87 ± 0.04	0.73 ± 0.10	0.70 ± 0.07	0.63 ± 0.05	0.48 ± 0.05
	20–40	1.03 ± 0.09	0.90 ± 0.08	0.84 ± 0.09	0.75 ± 0.05	0.73 ± 0.07	0.55 ± 0.06
	0–40	0.99 ± 0.08	0.88 ± 0.06	0.78 ± 0.10	0.73 ± 0.06	0.68 ± 0.08	0.52 ± 0.06
SOC (%)	0–20	1.67 ± 0.27	2.32 ± 0.49	3.10 ± 0.48	7.96 ± 2.44	9.31 ± 1.64	15.70 ± 1.74
	20–40	1.30 ± 0.19	1.64 ± 0.48	2.63 ± 0.53	4.77 ± 1.25	6.17 ± 1.02	12.02 ± 1.45
	0–40	1.49 ± 0.29	1.98 ± 0.58	2.87 ± 0.54	6.37 ± 2.49	7.74 ± 2.09	13.88 ± 2.47
TN (%)	0–20	0.16 ± 0.01	0.22 ± 0.04	0.27 ± 0.02	0.65 ± 0.18	0.78 ± 0.13	1.26 ± 0.27
	20–40	0.13 ± 0.01	0.17 ± 0.03	0.23 ± 0.03	0.38 ± 0.10	0.51 ± 0.09	0.94 ± 0.13
	0–40	0.14 ± 0.02	0.20 ± 0.04	0.25 ± 0.03	0.51 ± 0.20	0.64 ± 0.18	1.10 ± 0.26
pH	0–20	5.76 ± 0.05	5.50 ± 0.29	5.24 ± 0.47	4.08 ± 0.23	4.29 ± 0.41	5.02 ± 0.47
	20–40	5.80 ± 0.10	5.46 ± 0.45	5.24 ± 0.59	4.28 ± 0.17	4.26 ± 0.31	5.17 ± 0.54
	0–40	5.78 ± 0.08	5.48 ± 0.36	5.24 ± 0.50	4.18 ± 0.22	4.27 ± 0.35	5. 09 ± 0.49

Soil Temp. (°C)	0–20	25.60 ± 1.34	24.00 ± 2.83	22.40 ± 2.70	16.50 ± 0.55	15.43 ± 0.79	14.83 ± 0.41
	20–40	24.70 ± 1.30	22.80 ± 2.31	20.00 ± 2.00	16.33 ± 0.82	14.64 ± 0.94	14.50 ± 0.55
	0–40	25.15 ± 1.33	23.40 ± 2.51	21.20 ± 2.57	16.42 ± 0.67	15.04 ± 0.93	14.67± 0.49
Sand (%)	0–20	24.96 ± 7.71	21.74 ± 8.82	12.91 ± 2.60	24.98 ± 6.33	35.18 ± 7.44	58.90 ± 20.21
	20–40	15.52 ± 3.07	9.76 ± 2.61	12.16 ± 2.03	10.16 ± 3.99	16.52 ± 5.22	46.38 ± 13.99
	0–40	20.24 ± 7.44	15.75 ± 8.80	12.54 ± 2.23	17.57 ± 9.24	25.85 ± 11.48	52.64 ± 17.82
Silt (%)	0–20	38.48 ± 3.21	41.18 ± 6.09	50.53 ± 5.36	55.42 ± 2.16	51.55 ± 5.73	35.86 ± 16.96
	20–40	42.28 ± 3.09	44.39 ± 3.29	46.10 ± 5.11	56.00 ± 2.64	56.85 ± 3.86	45.74 ± 11.41
	0–40	40.38 ± 3.59	42.79 ± 4.91	48.32 ± 5.46	55.71 ± 2.32	54.20 ± 5.44	40.80 ± 14.71
Clay (%)	0–20	36.56 ± 4.75	37.07 ± 5.39	36.57 ± 4.12	19.61 ± 4.76	13.27 ± 2.47	5.24 ± 3.34
	20–40	42.19 ± 3.56	45.85 ± 5.49	41.73 ± 6.62	33.84 ± 3.40	26.62 ± 5.33	7.89 ± 2.65
	0–40	39.38 ± 4.95	41.46 ± 6.91	39.15 ± 5.87	26.72 ± 8.41	19.94 ± 7.99	6.56 ± 3.19
Texture	0–20	Clay Loam	Clay Loam	Silty Clay Loam	Silt Loam	Silt Loam	Sandy Loam
	20–40	Silty Clay	Silty Clay	Silty Clay	Silty Clay Loam	Silt Loam	Loam
	0–40	Clay Loam	Silty Clay	Silty Clay Loam	Silt Loam	Silt Loam	Sandy Loam

Note: 1000–1700m = farmland, 1700–2650= forestland

4.2.2 Variation of SOC and SOCS along the elevation gradient

The ANOVA model results showed elevation gradient and soil depth had a very highly significant effect on SOC and SOCS ($p<0.001$), while their interaction (elevation gradient x soil depth) had a highly significant effect ($p<0.01$) on SOC and a significant effect ($p<0.05$) SOCS on the eastern slopes of Mount Kenya *(*Table 8*)*.

Table 8: Two-way ANOVA results showing the effect of elevation gradient, soil depth and their interaction on SOC and SOCS on the eastern slopes of Mount Kenya.

		SOC			
Variables	**Df**	**Sum Square**	**F value**	**P-value**	**Significance**
Elevation gradient	5	1251.5	155.81	<0.001	***
Soil depth	1	74	46.24	<0.001	***
Elevation gradient x Soil depth	5	34.5	4.29	0.0022	**
Residuals	56	90.0			
		SOCS			
Variables	**Df**	**Sum Square**	**F value**	**P-value**	**Significance**
Elevation gradient	5	113030	120.37	<0.001	***
Soil depth	1	5402	28.76	<0.001	***
Elevation gradient x Soil depth	5	2605	2.78	0.026	*
Residuals	56	10517			

*Note: *, **, *** indicates significance at p < 0.05, p<0.01, and p<0.001 respectively.*

The highest mean SOC (15.70%) occurred in the 0–20 cm depth of upper forestland, while the lowest mean SOC (1.30%) was recorded in the 20–40 cm depth of the lower farmland elevation gradient *(Figure 20)*. SOC generally decreased down the elevation gradient and soil depth *(Figure 20)*.

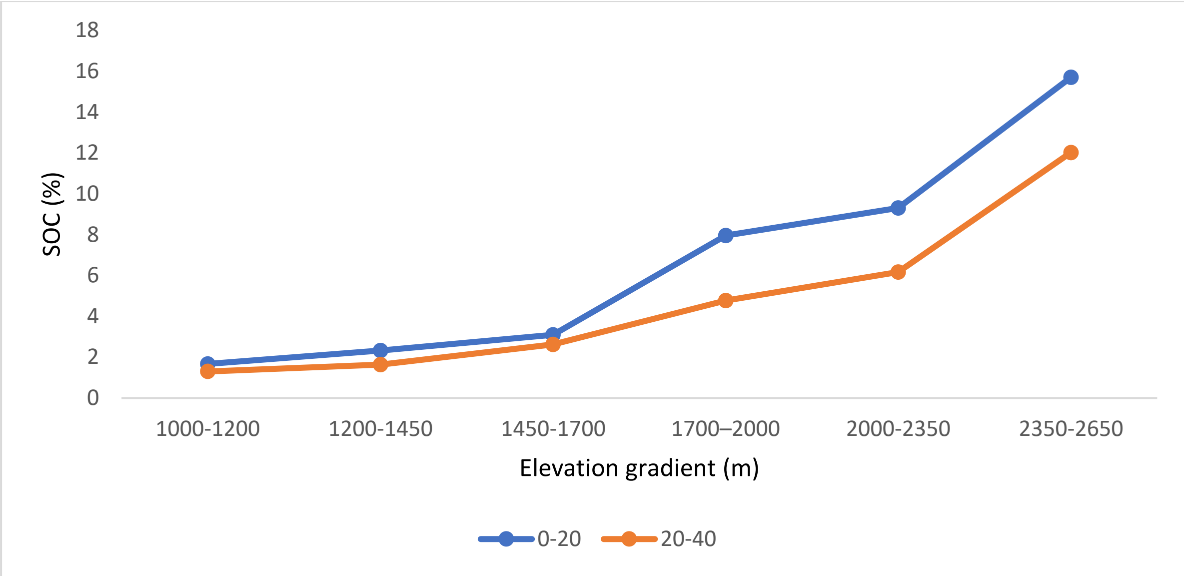

Figure 20: SOC at 0–20 and 20–40 cm depths based on elevation gradient in the study area

Relating to the elevation gradients, the maximum mean SOCS (151.27 ± 17.61 Mg ha^{-1}) was recorded in the 0–20 cm depth of the upper forestland, while the minimum mean SOCS (26.72 ± 4.68 Mg ha^{-1}) was found in the 20–40 cm depth in the lower farmland *(Figure 21)*. The mean aggregate (0–40 cm) SOCS based on elevation gradient were in the order of upper forestland > middle forestland > lower forestland > upper farmland > middle farmland > lower farmland *(Figure 21)*. Overall, the SOCS showed an increasing trend with increase in elevation and a decreasing trend with incremental soil depths.

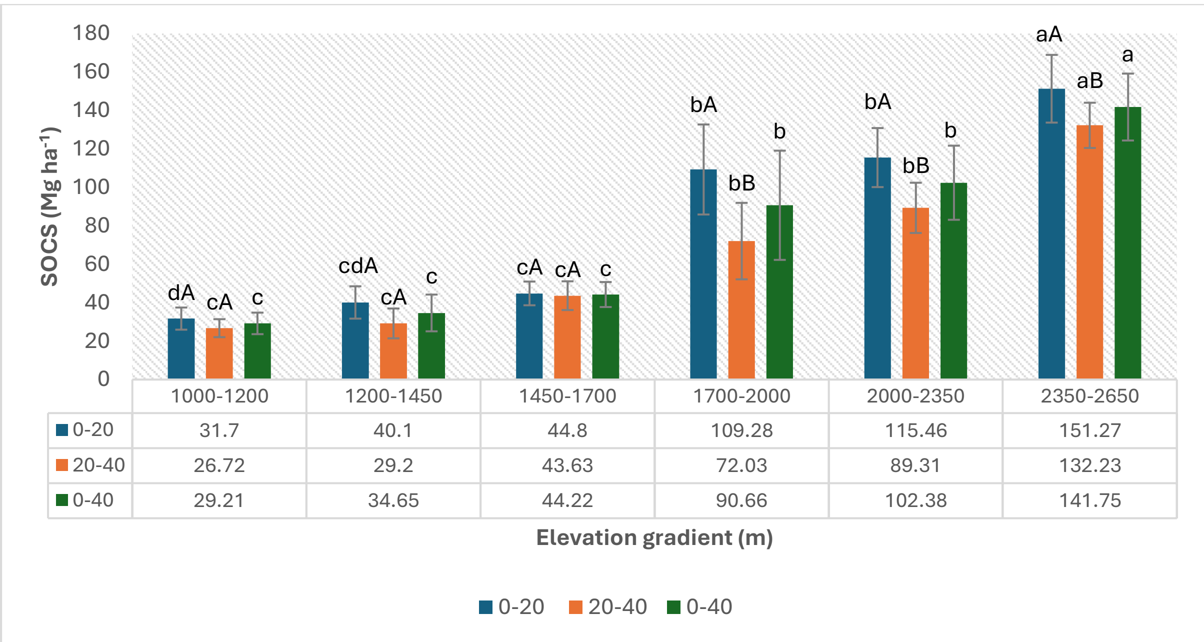

Figure 21: SOCS at 0–20, 20–40, 0–40 cm depths by elevation gradients in the study area

Note$_1$: 1000–1700m = farmland, 1700–2650= forestland

Note$_2$: Different lower cases indicate significant differences in SOCS between elevation gradients within the same soil depths, whereas different upper cases indicate significant differences in SOCS between soil depths within the same elevation gradient.

The SOCS showed a systematic upward trend along the elevation gradients in the eastern slopes of Mt Kenya. These results corroborate with findings by other researchers (Asrat et al., 2022; Njeru et al., 2017; Tsozué et al., 2019), which showed a similar increase in SOCS with an increase in elevation in similar tropical montane forest landscapes. Elevation plays a crucial role in the buildup and breakdown of SOC because of its significant impact on various co-varying environmental factors (Dad, 2019). Specifically, variations in climate at different elevations shape the composition and primary productivity of vegetation, influencing the amount and turnover of SOM through the regulation of soil water balance, soil erosion, soil temperatures, soil pH, soil texture, and geologic deposition processes (Dad, 2019; Tan et al., 2004; Wang et al., 2018). The increase in SOCS with elevation gradient is associated with increasing SOC with altitude due to higher OM inputs from above and belowground biomass and slow decomposition of SOM due to low temperatures at higher elevation ranges.

The overall mean SOC and SOCS values in the lower forestland were significantly lower than in the upper forestland. The presence of diverse indigenous vegetation species in the upper forestland, dense canopy, lower temperatures due to less exposure to sunlight, and higher precipitation contribute to greater SOM accumulation. The study area exhibited a significant altitudinal difference within short distances, which leads to great variation in climate and vegetation over relatively small distances. A characteristic change in vegetation was observed across altitudinal strata and among sites in the present study. Vegetation composition varied across the different elevation gradients, with a notable increase in plant diversity, tree abundance, and plant richness at higher elevations. Lower SOCS in lower forestland can be associated with less diverse vegetation species as it mostly comprised a mix of indigenous and exotic tree species. The lower forestland also depicted an open canopy as the trees were widely spaced, which results in lower litter input and less accumulation of SOM. Indications of human disturbances were also observed in the lower forestland as it is easily accessible by the communities bordering the forest compared to the middle and upper parts where human disturbances are rarely reported (Kenya Forest Service, 2010). Communities bordering the lower forestland elevation gradient often encroach into the forest for firewood collection, charcoal production, illegal timber logging, construction poles, and fodder harvesting (Kenya

Forest Service, 2010; Kenya Wildlife Service, 2010; Nature Kenya, 2019). This results in the continuous removal of potential SOM in the form of dead wood, twigs, litter, and trees, hence the lower SOC and SOCS recorded. This finding aligns with that by Tsozué et al. (2019) in Mount Bambouto, Central Africa, and Mariye et al. (2022) in the Ethiopian Central Highlands, where the accumulation of SOCS in the upper forest was attributed to longer vegetative growing periods with lesser human interference than in the lower forest, which showed diminished SOCS near human settlements. A study in the Mount Marsabit Forest Reserve, a sub-humid montane forest in northern Kenya, also established that SOCS was concentrated in the least disturbed forest areas, while reduced SOCS were observed in the disturbed forest areas with pronounced anthropogenic activities (Muhati et al., 2018).

SOCS values in the lower farmland gradient were significantly lower than those in the upper farmland category. The upper farmland elevation is predominantly a tea-growing zone with higher precipitation than the other farmland elevation zones. Tea bushes form a good closed canopy, reducing SOC losses through erosion, while tea management practices like pruning return a substantial amount of tea biomass back to the soil (Kamoni et al., 2007). A comparative study in neighbouring Embu County equally revealed higher SOCS in forests and tea growing zones compared to rotation crop zones due to higher input of vegetation matter at the soil surface (Segnini et al., 2019). Lower rainfall amounts are also experienced in the lower farmland elevation compared to the middle and upper farmland. Additionally, the quick mineralization of crop residues on the surface soils contributes to lower amounts of labile soil carbon in low-lying areas experiencing high temperatures and limited soil moisture (Njeru et al., 2017).

4.3 Farmers adoption of RSMPs

4.3.1 Demographic, socio-economic, and farm characteristics

The study findings show that slightly more than half (56%) of the respondents were male, while 44% were female *(Table 9)*. The HH heads had an average age of 52 years. The majority (78.5%) of the respondents were married, and the average HH size in the study area was 5 people.

Most HHs reported a monthly income of between 6,000 and 20,000 Kenyan shillings (KES). The average farm size in the study area was 1.71 acres, with an average distance from homestead of 79.43 m. Close to half of the farmers (47.0%) had access to credit, and about 70% had access to agricultural extension services. Most farmers (60.7%) relied on family labour for their day-to-day farming activities. About 42.0% of the respondents were residents of the Upper Midland Agro Ecological Zone (UM AEZ) of Chogoria *(Table 9)*.

Table 9: Respondents' socio-economic, demographic, and farm characteristics on the eastern slopes of Mount Kenya.

Variables	**Characteristic**	**(n=150)**	**(%)**	**Min**	**Max**	**Mean ($\bar{x}$)**	**Std Dev (σ)**
Gender	Male	84	56				
	Female	66	44				
Age (years)				26	78	51.58	10.38
Marital status	Single	7	4.7				
	Married	118	78.7				
	Widowed	18	12.1				
	Divorced	4	2.7				
	Separated	3	2				
Level of education	No formal education	6	4				
	Primary	70	46.7				
	Secondary	58	38.7				
	Tertiary	16	10.7				
Household size				1	9	4.54	1.35
Average monthly income (KES)	<5,000	57	38				
	6,000-20,000	66	44				
	21,000-35,000	22	14.7				
	36,000-50,000	4	2.7				
	>50,000	1	0.7				
Access to credit	Yes	71	47.33				
	No	79	52.67				
Access to extension	Yes	105	70				
	No	45	30				
Farm size (acres)				0.2	7	1.71	1.09
Distance of farm from homestead (m)				2	1000	79.43	152.84
UM AEZ	Yes	63	42				
	No	87	58				
Farm labour	Family	91	60.7				
	Hired	59	39.33				

Note: UM AEZ = Upper Midland Agro Ecological Zone; KES= Kenyan shillings

The dominance of male respondents in the study area is because in most Sub-Saharan Africa (SSA) communities, men are the de facto HH heads in charge of decision making (Mugwe et al., 2009; Mwaura et al., 2021) although in some cases decisions can be made or greatly influenced by women even though they are not the HH heads (Nchanji et al., 2023). Women also have land use rights and execute most of the farm and household chores. Similar findings were noted in studies conducted in rural Kenya (Mugwe et al., 2009; Wawire et al., 2021), Tanzania (Mbaga-Semgalawe & Folmer, 2000) and Ethiopia (Belayneh, 2023). The youngest respondent was 26 years, while the oldest was 78 years with the average HH age being 52 years. Age is one of the factors affecting the ownership and ability to access production resources such as land, inputs, and capital, as well as their commitment to RSMPs investments (Byamukama et al., 2019). The elderly have more access to land and agricultural resources because in the study region, land is mostly passed from one generation to another by inheritance (Mugwe et al., 2009). According to the Ministry of Agriculture report (Ministry of Agriculture Livestock and Fisheries, 2017), about 61% of households headed by youths in TNC earn their income from farm wages. This underlines the importance of the agriculture sector for youth employment and livelihoods in the study region in as much as land ownership by the youth is a notable challenge. Most respondents in the study area had attained either primary or secondary education. Educated farmers can read and write and are presumed to have a higher capacity to capture and synthesize technical information characteristic of some RSMPs (Marenya & Barrett, 2007). A study by Asfew et al. (2023) also revealed that educated farmers offer more cooperation to extension workers and are more willing to adopt new RSMPs than uneducated farmers.

4.3.3 Recommended Soil Management Practices Adoption

A total of 98 farmers (65.33%) had adopted at least one RSMP on their farms, while the remaining 52 (34.67%) had not at the time of this study. Amongst the three wards, Chogoria, which lies in the UM AEZ, had the most adopters of RSMPs (76.19%), followed by Ganga (57.78%) which is found in between the UM and Lower Midland (LM) AEZ, while Mwimbi (54.76%) located in the LM AEZ had the least adopters *(Figure 22)*.

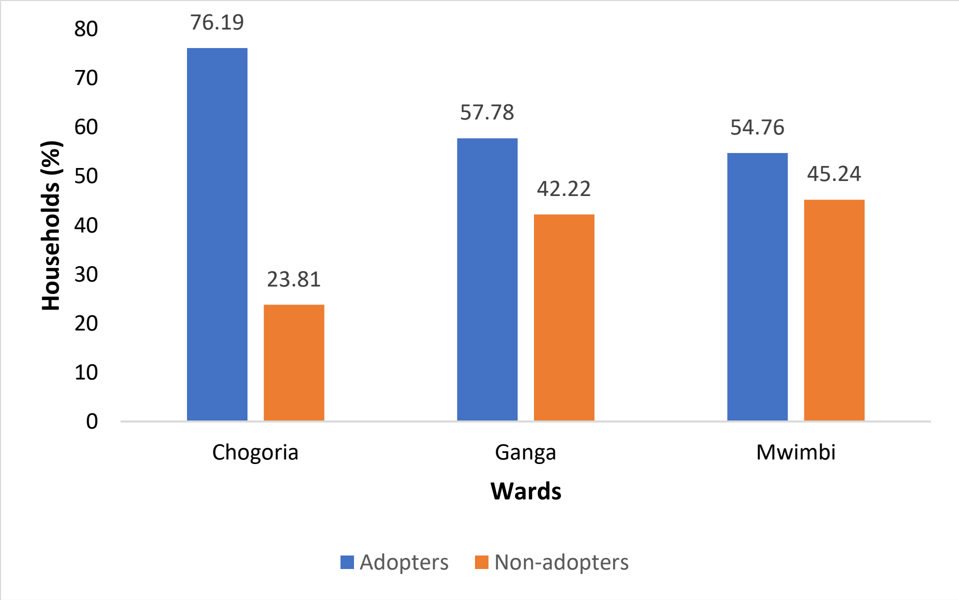

Figure 22: Adoption of RSMPs per ward in the study area

Similar findings were reported by Mairura et al. (2022a), who also stratified their study area according to AEZs and established that the farmers' adoption rate of soil fertility management technologies was higher in the UM AEZs than in the LM AEZs. Nyangena. (2008) also affirms that the location of a farm on the toposequence is a key determinant of RSMPs adoption by farmers. Farmers in in the UM AEZ perceived soil erosion as a major farming constraint which necessitated them to adopt conservation agriculture like terraces and agroforestry practices for control of soil erosion (Rotich et al., 2024). This finding is in tandem with that carried out in rural Ethiopia which showed more farmers from the highland zones adopted conservation agriculture in relation to those from the lowland zones due to perceived erosion (Yirga & Hassan, 2010).

A total of fifteen distinct RSMPs were documented in the study area *(Figure 23)*. Multiple responses from the HH heads showed that the top three most adopted RSMPs included terraces (54.67%), minimum tillage (43.33%), and crop rotation (35.33%), while the three least practiced conservation measures were stone bunds (0.67%), tied ridges (1.33%) and ditches (1.33%).

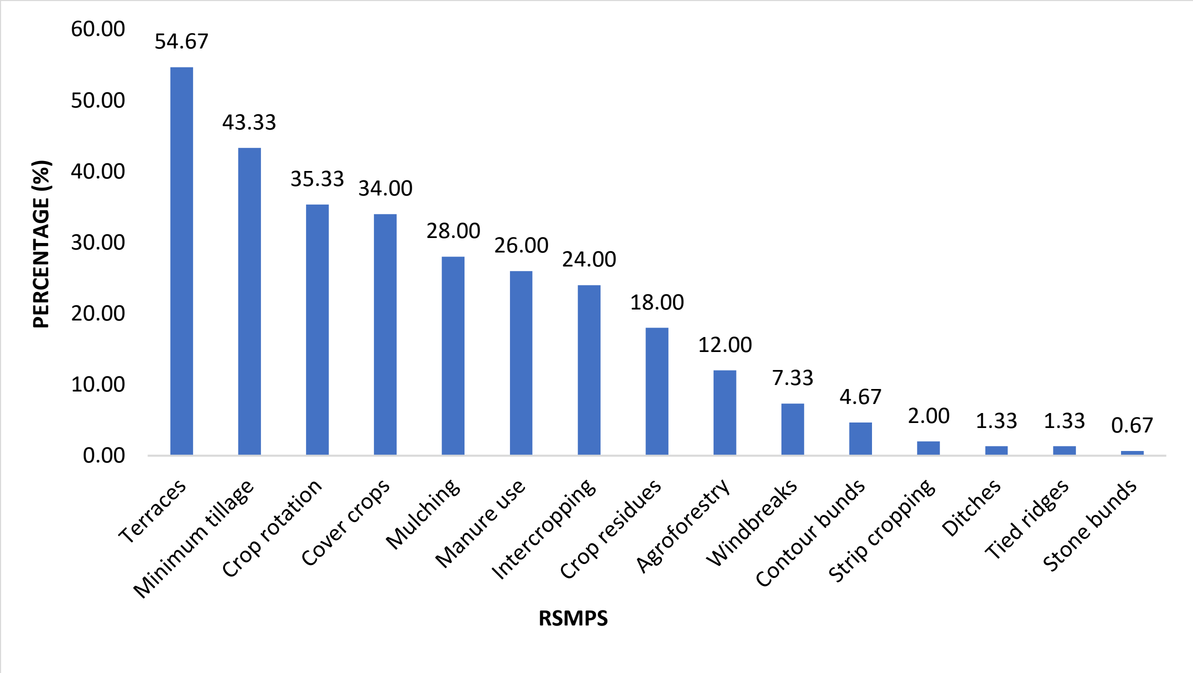

Figure 23: Types of RSMPs in the study area

From the results *(Figure 23)*, it was evident that vegetative and agronomic practices were dominant over structural RSMPs in the study area. This observation can be linked to the low adoption costs of vegetative and agronomic practices compared to structural measures, which require high initial capital and labour input. In SSA, agronomic and vegetative RSMPs have been applied widely due to their low cost of adoption (Gachene et al., 2020). The unique high adoption of terraces (a structural measure) in the study area can be attributed to it being an indigenous technology among Eastern African (EA) communities and its effectiveness in reducing surface runoff (70-92%), especially in steep slopes (Gachene et al., 2020). Terracing and reduced tillage can reverse elevated rates of topsoil decline from agricultural practices across Kenya (Feeney et al., 2023). An interview with Community-Based Organization (CBO) officer revealed that the implementation of terraces in the study area dates back to the 1960s after the initial introduction by the colonial government. *"The implementation of terraces in this area is common as it dates back to the 1960s, when they were initially introduced by the colonial government authorities to curb soil erosion"* shared a CBO official during the interview. Destaw and Fenta. (2021) further assert that in highland and midland areas characterized by medium to steep slopes, farmers are more likely to adopt terracing as a RSMP and climate change adaptation strategy. Structural and vegetative RSMPs have proven effective in tackling water runoff and erosion when properly implemented (Diop et al., 2022).

Among the adopters, the majority (76.53%) implemented a combination of two or more RSMPs, while the remaining 23.47% implemented only one type of practice (see examples from the field observation in *Figure 24*). An interview with agricultural extension officers revealed that a combination of more than one RSMP is advisable as they complement each other. *"Most smallholder farmers combine more than one RSMPs since they complement each other and also as way of getting maximum production from their lands considering the small sizes of land"* explained one of the agricultural extension officers during the interview. This combination results in more effective outcomes of reducing erosion, conserving water for plant use, and improving soil fertility, especially when practices like manure application, agroforestry, and crop residues are combined. These findings contrast those of Mwanake et al. (2023), carried out in the transboundary region of Kenya and Uganda, who found out that most farmers applied a single RSMP as most farms in the region were highly fragmented.

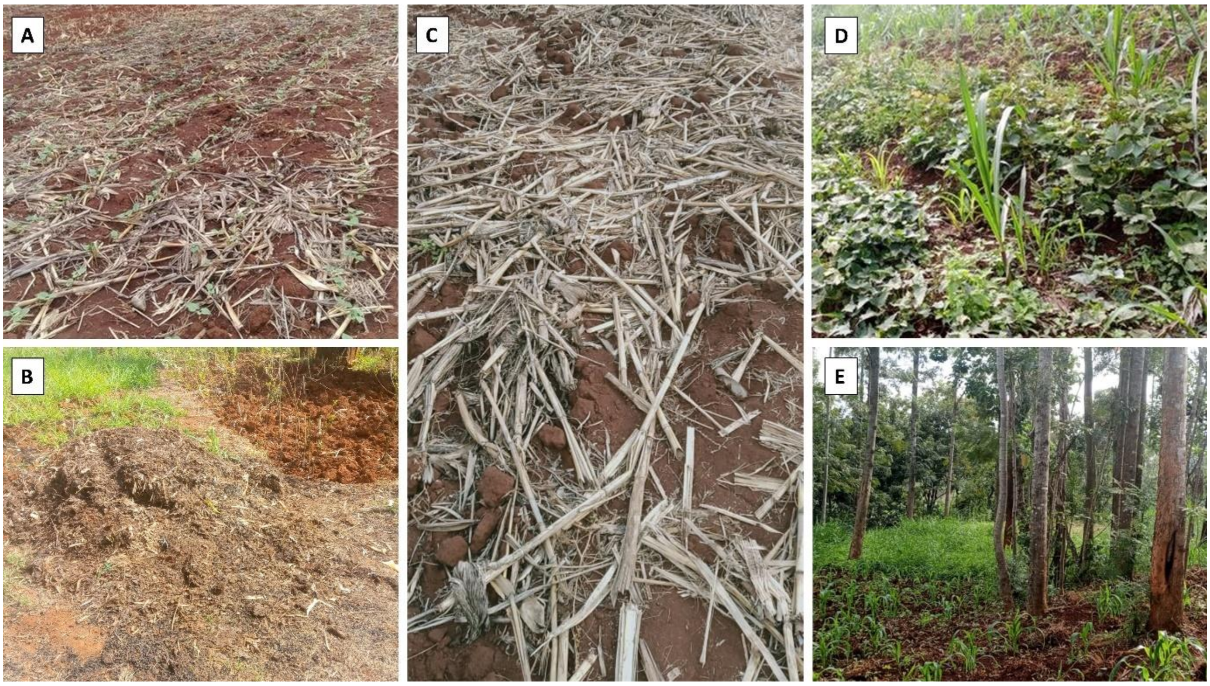

*Figure 24: Select RSMPs in the study area**:** A = Mulching, B = Manure, C = Crop residues, D = Cover crops, E = Agroforestry*

4.3.4 Determinants of RSMPs adoption

The correlation analysis results are depicted in the correlation coefficient heat map *(Figure 25)*. All the explanatory variables had a correlation coefficient of less than 0.8, implying a non-existence of multicollinearity in the model. Based on the correlation matrix heat map, most variables displayed weak correlation with a correlation coefficient ranging between 0 and 0.45 as indicated by green colour *(Figure 25)*.

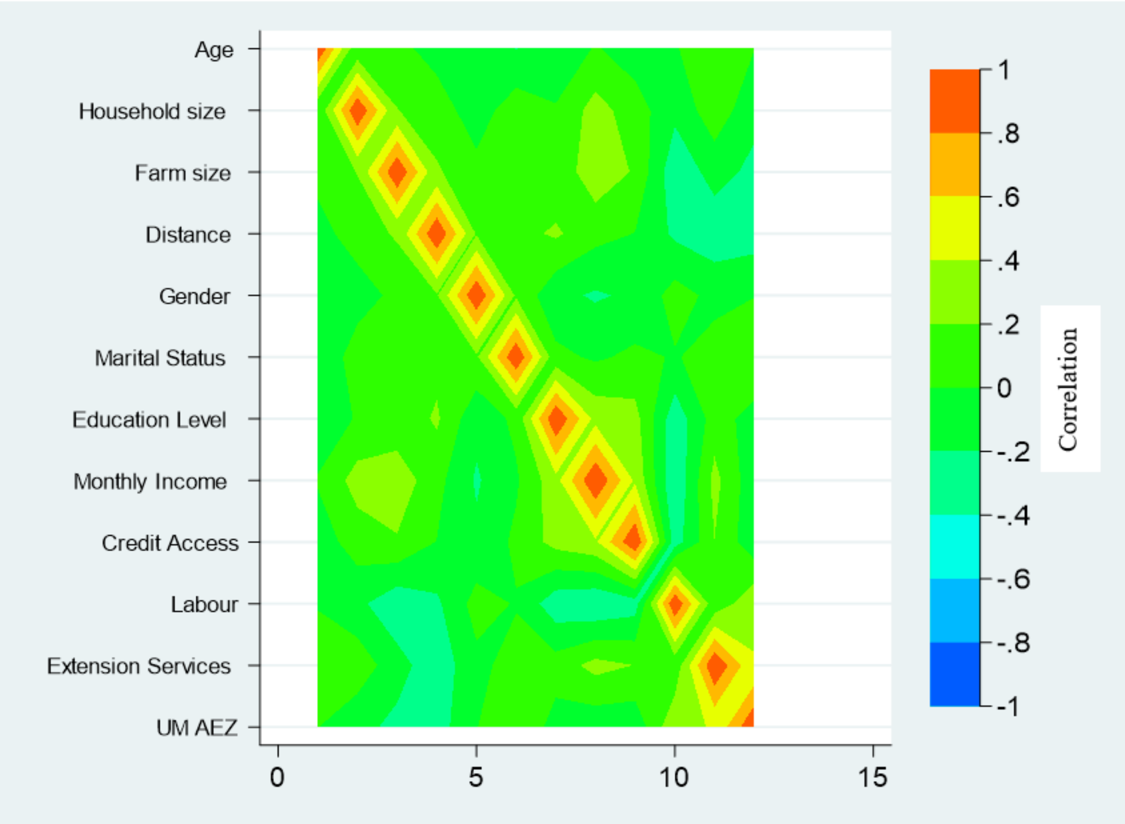

Figure 25: Correlation matrix heat map for model multicollinearity test

The VIF results *(Table 10)* showed that the VIF and tolerance values for all selected variables were less than 5 and greater than 0.1, respectively. These collaboratively signify that including the explanatory variables together doesn't result in strong multicollinearity in the subsequent regression models.

Table 10: Multicollinearity test results showing the VIF and tolerance values for the selected variables in the study area.

Variables	Variable type	Variable description	Measurement	RSMP Adoption VIF	1/VIF
Age	Continuous	Age of household head	Years	1.16	0.862
Household size	Discrete	Number of family members in the household	Whole numbers (1, 2, 3...)	1.19	0.837
Farm size	Continuous	Household farm size	Acres	1.36	0.737
Distance	Continuous	Distance between homestead and farm	Meters	1.40	0.713
Gender	Categorical	Sex of household head	Dummy (female=0, male=1)	1.20	0.832
Marital status	Categorical	Marital status of household head	Dummy (unmarried=0, married=1)	1.21	0.830
Level of education	Categorical	Household head's education level	Dummy (no formal=0, formal=1)	1.37	0.729
Average monthly income (KES)	Categorical	Household average monthly income in KES	Dummy (<5000=0, >5000=1)	1.68	0.594
Access to credit	Categorical	Household access to credit	Dummy (no=0, yes=1)	1.32	0.755
Labour type	Categorical	Type of labor used on farm	Dummy (family=0, hired=1)	1.51	0.660
Access to extension	Categorical	Household access to agricultural extension services	Dummy (no=0, yes=1)	1.72	0.583
UM AEZ	Categorical	Upper Midland Agro-Ecological Zone type	Dummy (no=0, yes=1)	1.61	0.620

** KES = Kenyan shilling; UM AEZ= Upper Midland Agro-ecological zone*

The findings of the predicted binary logistic regression model coefficient estimates, marginal effect, standard error, and the associated significance values are shown in *Table 11*. The likelihood ratio test value (-84.34) indicates that the binary logit model and the selected explanatory variables fit the data correctly, signifying that log odds, probability of adopting RSMPs, and the included independent variables collectively contribute to significant explanation of HH determinants. Although individually, some explanatory variables were insignificant, the pseudo-R^2 value (0.134), with a significantly (P=0.010<0.05) higher LR Chi-square value (26.17) finding pointed out that the estimated model has sufficient explanatory power, hence the appropriateness of the model information.

Table 11: Summary of binary logistic regression model output for factors influencing the adoption of RSMPs in the study area.

Variable	Variable type	Variable description	Measurement	Coeff	Marginal Effects	Std. Err	Z	P-value >|Z|
Age	Continuous	Household head age	Years	**-0.039****	**-0.007****	0.020	-1.96	0.050
Household size	Discrete	Household size	Whole numbers (1, 2...)	0.091	0.017	0.150	0.60	0.545
Farm size	Continuous	Household farm size	Acres	**0.641****	**0.122****	0.259	2.47	0.013
Distance	Continuous	Distance from homestead to farm	Meters	**-0.003****	**-0.001****	0.002	-2.09	0.036
Gender	Categorical	Household head gender	Dummy (female=0, male=1)	-0.025	-0.005	0.400	-0.06	0.950
Marital status	Categorical	Household head marital status	Dummy (unmarried=0, married=1)	-0.104	-0.020	0.449	-0.23	0.817
Education	Categorical	Household level of education	Dummy (no formal=0, formal=1)	0.330	0.063	0.301	1.10	0.273
Income	Categorical	Household average monthly income	Dummy (<5000=0, >5000=1)	0.242	0.046	0.258	0.94	0.348
Access to credit	Categorical	Household access to credit	Dummy (no=0, yes=1)	0.599	0.114	0.472	1.27	0.205
Labour	Categorical	Household labour type	Dummy (family=0, hired=1)	-0.160	-0.031	0.403	-0.40	0.691
Access to extension	Categorical	Household access to extension services	Dummy (no=0, yes=1)	0.192	0.037	0.550	0.35	0.727
	Categorical	Upper Midland Agroecological zone	Dummy (no=0, yes=1)	**1.341****	**0.256****	0.519	2.58	0.010
Constant				-0.418		2.001	-0.21	0.835
LR $Chi^2(12)$				26.17				
Prob $>Chi^2$				0.010				
Pseudo R^2				0.134				
Log Likelihood				-84.34				
No. of Observations				150				

*Note: *** p<0.01; **p<0.05; *p<0.1; UM AEZ= Upper Midland Agro Ecological zone*

The HH head's age, farm size, distance from homestead to farm, and HHs located in UM AEZ were the significant predictors of HH RSMPs adoption at 5% significance level. Accordingly, HH age had a negative significant influence on HH RSMPs adoption (β= -0.039; P=0.050≤0.05). The marginal effect indicates that an increase in HH head's age by 1 year leads to a decline in the probability of adopting RSMPs by 0.7%, holding all other variables constant. This can be alluded to the fact that as farmers age, they become weary and can no longer provide the intensive labour required for implementing labour intensive RSMPs. On the contrary, young farmers are more energetic and willing to invest in RSMPs whose benefits may not be realised immediately but in the long run. This finding is in line with that by Nyangena. (2008); Asfaw and Neka. (2017); Degfe et al. (2023), who reported that HH head's age has a significant negative influence on the adoption of RSMPs.

The findings also indicated a significant negative effect of distance between homesteads and farms on the adoption of RSMPs; where an increase in distance by 1 unit would result in a decline in HH adoption of RSMP (β= -0.003; P=0.036<0.05). The marginal effect *(Table 11)* shows that an increase in distance from homestead to farm by 1 m reduces the probability of adopting RSMPs by 0.1% at a 5% significance level. This finding can be alluded to the fact that most smallholder farmers would want to invest more in nearby farms as distant farms disrupt or interfere with their daily homestead chores and other farm management practices. These findings align with the findings observed by previous studies (Moges and Taye, 2017; Wordofa et al., 2020; Degfe et al., 2023), which deduced that the longer the distance between homestead and farms, the lower the likelihood of adopting RSMPs. The negative effect can also be due to the intensity of labour required to implement some of the RSMPs like transporting the bulky manure to distant farm location, and the preferential crop treatment. This makes crops grown in the remote fields of the farm less important and in the end receive minimum management attention by the farmers.

The farm size showed a strong significant positive influence on the adoption of RSMPs (β= 0.641; P=0.013<0.05). Farmers with larger tracks of cultivatable land are more likely to adopt new RSMPs, more so the physical practices. This is because farmers perceived long-term farm benefits can be achieved by implementing physical RSMPs structures, which in most cases consume significant portions of the land. Therefore, farmers with small farm sizes are unwilling to adopt such RSMPs because the structures can further reduce the land size, thereby lowering agricultural output. On the contrary, farmers holding large sizes of land do not pay much attention to the land lost. As indicated by the marginal effect, an increase in the size of the land by one acre implies that the HH's adoption of RSMPs increases by 12.2% at a 5% significance level. In line with this observation, Kifle et al. (2016) and Belayneh. (2023) deduced that farmers with large sizes of land have a greater likelihood of adopting RSMPs compared to the farmers with small land sizes. Similar studies in rural Ethiopia and the Eastern and Southern Regions of Cameroon revealed that HHs with large farm sizes are prone to accepting new practices because they can devote a section of their land to testing emerging innovations, while farmers with smaller farm sizes are less willing to do so (Gebremariam & Tesfaye, 2018; Ngaiwi et al., 2023).

The UM AEZ (Chogoria) showed a strong significant positive influence on the adoption of RSMPs (β= 1.341; P=0.019<0.05). This implies that HHs residing in highland (Chogoria) regions have a higher likelihood (25.6%) of adopting RSMPs compared to HHs in the middle (Ganga) and lowland (Mwimbi) regions. This is due to the high and frequent precipitations received and the steep nature of the terrain in the highlands. Steeper slopes have a higher vulnerability to erosion and landslides (Nyangena, 2008). Consequently, farmers who operate on farmlands with steep slopes are more likely to adopt RSMPs due to the severity of soil erosion. Similarly, Amsalu et al. (2007); Teshome et al. (2016); and Sileshi et al. (2019) observed that HHs owning farms in highland regions are more likely to adopt RSMPs compared to the HHs operating on farms located in the middle or lowland regions as they have higher perception rate of probable soil erosion.

While dominant literature has documented significant contribution of household income, level of education, access to credit and extension services to the adoption of technology, some studies have similarly pointed out negative or insignificant contribution of the aforementioned social variables too (Chang et al., 2024; Minten & Barrett, 2008; Mishra et al., 2018; Nyangena, 2008). It is possible that experience, indigenous knowledge, or mentorship from peers within the farming community compensates for formal education in this context, reducing its role in adoption decisions (Nyangena, 2008). As for the income, if most farmers have an almost similar financial standing, the impact of income on adoption decisions may be diminished (Minten & Barrett, 2008).

4.3.5 Challenges facing the adoption of RSMPs

The farmers who carried out RSMPs indicated they faced numerous challenges in the adoption and maintenance of the said practices (*Figure 26*). The top three challenges encompassed financial constraints (76.53%), Inadequate labour (62.24%), and competing uses (41.83%).

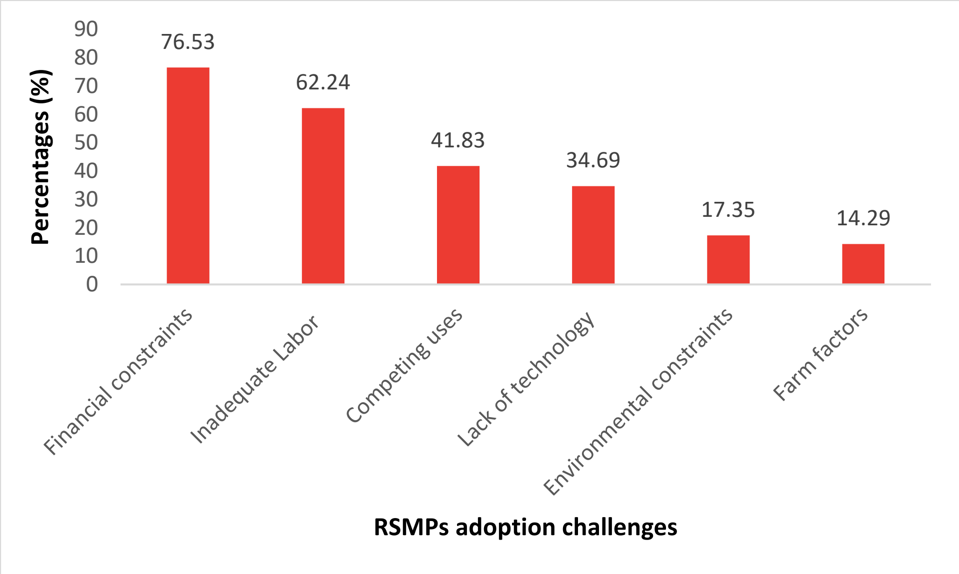

Figure 26. Challenges facing the adoption of RSMPs in the study area

The implementation and maintenance of RSMPs, especially structural measures, often require high startup capital and labour inputs. This can be challenging for smallholder farmers who, in most cases, have limited resources. This can result in low adoption, improper implementation, or poor maintenance, thereby failing to meet the desired goals. This finding resonates with that of Bojago et al. (2022), who identified a lack of capital and material support as key challenges facing the implementation of RSMPs in Offa Woreda, Wolaita Zone, Ethiopia. Technical knowledge and equipment are also necessary for the proper implementation of most RSMPs. In the Wenago district of southern Ethiopia, lack of technical knowledge and skills was reported as a limitation in the adoption of improved and introduced RSMPs by more than half of the interviewed farmers (Meresa et al., 2023). During the interviews one agricultural extension officer lamented insufficient resources allocation and personnel to effectively disseminate RSMPs adoption education and training. *"We have a limited budgetary allocation from the County government for farmers' education and training on the implementation of the RSMPs. Furthermore, the area allocated to one extension officer is too big to cover for a meaningful impact"* said the extension officer. Limited institutional capacity in terms of staffing, equipment, and resources therefore contributes to the low adoption of RSMPs in the study area.

Competing uses of crop biomass was also another challenge facing the implementation of RSMPs. It has been established that RSMPs are not effective on sites where crop residues are regularly removed for fodder, traditional or modern fuels, and other competing uses (Lal, 2011). Local soil and climatic conditions, including soil type, precipitation amount and distribution, temperature, and slope, determine the type of RSMPs and viability of field operations. In arid and semiarid regions, intercropping may be lead to competition for water and nutrients between the plant cover and the main crop, while in rice fields characterised by clay soils which are water-logged, minimum tillage is hampered (Francaviglia et al., 2023). Farm factors like insecure land tenure was another challenge in adopting RSMPs in the study area since some farmers had leased the land for a short period. A report by the Kenyan Ministry of Agriculture (Republic of Kenya, 2020) indicates that farmers may be unwilling to invest in long-term structural RSMPs such as terracing and agroforestry if they are not sure of reaping the benefits from such work in the long run.

4.4 Impacts of management practices on SOCS

An ANOVA was conducted in the R environment to assess the impacts of the various RSMPs on SOCS, and the results summarized in *Table 12.*

Table 12: Summary of the ANOVA results showing the impacts of RSMPs on SOCS in the study area.

RSMPs	Df	Sum Sq	F value	Pr (>F)	Significance
Minimum tillage	1	0.0	0.000	0.98657	
Terraces	1	0.0	0.000	0.99087	
Manure	1	212.8	6.453	**0.02263**	*
Cover crops	1	6.5	0.199	0.66222	
Intercropping	1	202.9	6.152	**0.02547**	*
Crop residue	1	444.0	13.465	**0.00228**	**
Crop rotation	1	221.9	6.728	**0.02035**	*
Agroforestry	1	381.6	11.571	**0.00394**	**
Windbreaks	1	47.0	1.425	0.25116	
Contour bunds	1	33.8	1.024	0.32764	
Ditches	1	42.4	1.286	0.27464	
Mulching	1	241.3	7.318	**0.01629**	*
Stone bunds	1	71.7	2.175	0.16091	
Tied ridges	1	237.7	7.208	**0.01697**	*
Residuals	15	494.6			

*Note: * = significant at 0.05; ** = significant at 0.01*

The analysis revealed that agroforestry and crop residue management had a highly significant impact on SOCS ($p < 0.01$). This indicates that farms incorporating crop residues into the soil tend to maintain higher levels of SOC, emphasizing the critical role of returning organic material to the soil for enhanced carbon content. Similarly, integrating trees into farming systems significantly boosts SOCS, highlighting the benefits of agroforestry in improving soil health. This finding corroborates with that by Wawire et al. (2021) which showed agroforestry, manure application, and crop residue retention positively influenced the soil quality in the Mount Kenya east region. Studies carried out in western Kenya and the drylands of eastern Kenya also revealed agroforestry practices significantly increases the SOC contents in the soil due to litter addition and soil protection role of the agroforestry trees (Kibet et al., 2022; Syano et al., 2023).

Other practices, including manure application, mulching, intercropping, crop rotation, and tied ridges, also showed a statistically significant effect on SOCS ($p < 0.05$). Previous researchers have correspondingly recognized the application of organic manure and crop residue use as some of the key RSMPs for enhancing SOCS and soil fertility (Oechaiyaphum et al., 2020; WANG et al., 2017). Intercropping, which involves growing multiple crops together, may enhance SOC levels through increased biodiversity and better soil coverage. Crop rotation improves soil structure, nutrient cycling, and carbon storage, while mulching, which involves covering the soil with organic materials, helps retain moisture, reduce erosion, and contribute organic matter to the soil. A systematic review of soil management practices showed that different crop rotation schemes significantly influenced the SOCS (Söderström et al., 2014). Tied ridges further promote SOC accumulation by improving water retention and minimizing soil erosion. This finding is supported by Ndung'u et al. (2023) who reported that tied ridges significantly improved soil fertility and crop yields in the semiarid Tharaka Nithi South Sub-County of Kenya.

On the other hand, RSMPs such as terraces, windbreaks, contour bunds, ditches, stone bunds, and cover crops did not exhibit significant effects on SOCS ($p > 0.05$). While these practices did not show strong influence from this analysis, they may still offer localized benefits or synergistic effects when combined with other RSMPs.

4.5 Farmers SOM knowledge and perceived benefits

When asked if they knew what SOC was, none of the farmers gave an affirmative response. On the other hand, 76.70% of the respondents were knowledgeable about SOM, while 23.30% were not. SOM was referred to as *umbuthi* or *thuumu* in the local Gichuka dialect and *mboji* in the national Swahili language. As for the indicators of soils with high SOM content, the farmers listed four main indicators, namely fine soil texture (63.48%), dark or black colour (59.13%), high plant diversity (52.17%), and a high number of soil macro-organisms (27.83%) *(Figure 27)*.

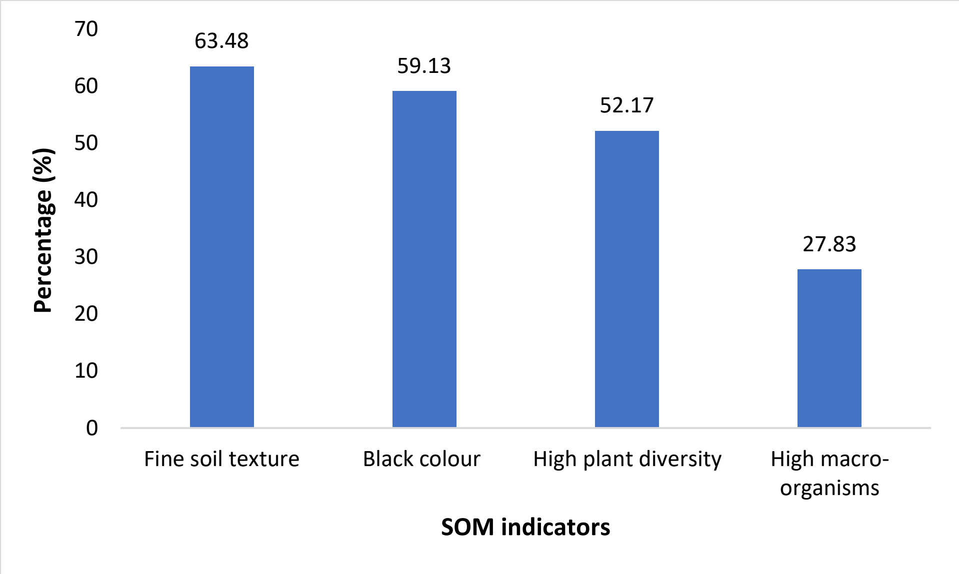

Figure 27: Indicators of soils with high SOM content (farmers' perception)

These findings agree with that by Wawire et al. (2021) in the upper eastern region of Kenya, where farmers listed dark-coloured soils, the presence of earthworms, the existence of some weed species, and good soil workability as key indicators of fertile soils with high SOM content. Farmers in the Ashanti region of Ghana likewise associated dark/black colour and fine soil texture with high SOM content (Adiyah et al., 2021). Respondents from six regions of Ghana assessed the SOM status by the dark colour of the soil, soft structure and the abundance of vegetation (Quansah et al., 2001). A study carried out in the municipality of Camaquã-Rio Grande do Sul, Brazil revealed farmers named presence of earthworms, black colour, spontaneous vegetation, better root development, and soil friability as indicators of SOM (Lima et al., 2011).

When asked about the perceived benefits of high SOM content in the soil, most of the respondents (97.39%) listed high crop yields as the key benefit. About 66.96% of the farmers associated SOM with control of soil erosion, improved soil structure (65.22%), while only 23.48% acknowledged the importance of SOM in climate change mitigation (*Figure 28*). Similar findings were reported among smallholder farmers in the Ashanti region of Ghana (Adiyah et al., 2021). A study carried out in Bangladesh and Ghana equally showed that farmers linked SOM with improved soil structure, increased crop yields, reduced production cost, improved soil temperature, improved plant growth, and increased soil water-holding capacity (Hossain, 2001; Quansah et al., 2001).

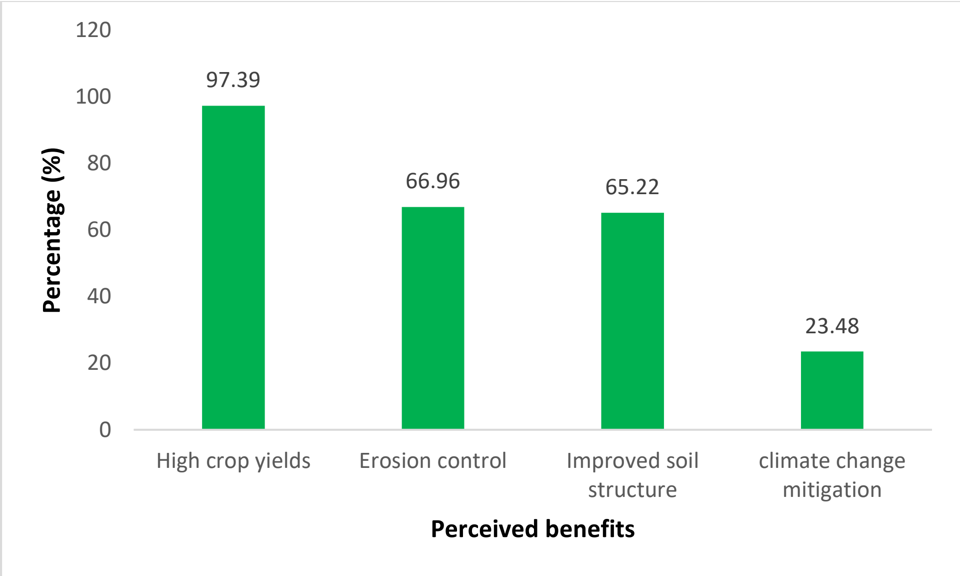

Figure 28: Farmers' perceived benefits of SOM on the eastern slopes of Mount Kenya

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The overall objective of this study was to investigate the influence of elevation, land use, and management practices on SOCS on the eastern slopes of Mount Kenya. The first objective of this study was to investigate the effects of land use type on SOCS in the Mount Kenya East region. There were significant variations in selected soil physicochemical properties (BD, pH, SOC, TN, soil temperature, clay, silt and sand) between the forestland and farmland. The results also showed a significant influence of land use on SOCS as higher SOC values were recorded for both the topsoil (0–20 cm) and subsoil (20–40 cm) in the forestland compared to farmland under the present conditions. The mean SOC and SOCS in the forestland and farmland was 9.24 ± 3.96%; 111.11± 30.49 Mg ha^{-1} and 2.11 ± 0.75; 36.02 ± 9.54 Mg ha^{-1} respectively. These variations can be attributed to differences in vegetation types, soil types, climatic conditions and human activities between the two land use types. With regards to the vertical distribution, SOCS in the topsoil were generally higher than in the subsoil for both land use types. This observation can be linked to the continuous addition of undecayed, and partially decomposed plant and animal remains to the topsoil. The study findings emphasize the substantial impact of land use on SOCS, highlighting the crucial role of the Mt Kenya forest in maintaining high levels of SOCS, which is integral for soil health and climate change mitigation. It also shows the potential of the farmlands in the study area for carbon sequestration.

The second objective of the study was to assess the influence of elevation on SOCS in the eastern slopes of Mt Kenya. SOCS showed a systematic ascending trend with increasing elevation, peaking at the upper forestland, which represented the highest elevation gradient of the study area. Collectively, it was observed that a decrease in precipitation, an increase in temperature, and land use intensification were linked with declining SOCS down the elevation gradient. The observed correlations between SOCS and other soil properties and environmental variables further underscore the intricate relationships within the soil system and with the environment.

The third objective of this study sought to characterise RSMPs in the study area and assess the determinants of adoption and challenges of adopting RSMPs for enhanced SOCS and reduced SOM loss. The household demographic, socioeconomic and farm characteristics were first captured before establishing the factors influencing the adoption of RSMPs. The study characterised fifteen different vegetative, agronomic, and structural RSMPs implemented by smallholder farmers singly or in combination with other practices in the study area. Farmers' adoption of these practices was influenced positively by farm size and agroecological zonation (AEZ) while the distance from homesteads to farms and the age of the HH heads negatively influenced the adoption of RSMPs. The adopters of RSMPs also encountered financial, labour, environmental, and infrastructural-related challenges in implementing the said practices. These challenges and the uneven adoption of RSMPs constrain SOC sequestration in the region. Findings from this study are pertinent for shaping policies that address environmental, agricultural, and socio-economic challenges in TNC and other regions with similar settings.

The fourth objective of the present study was to assess the influence of RSMPs on SOCS. The results revealed crop residue management, agroforestry, manure application, mulching, intercropping, crop rotation, and tied ridges as management practices having a significant influence on SOCS in the study area.

The fifth objective of this study was to assess farmers' SOC and SOM knowledge and perceived benefits of SOM. None of the farmers knew about SOC while about 77% of the farmers were knowledgeable about SOM and perceived it to be important for high crop yield, erosion control, improving the soil structure and climate change mitigation. According to the farmers, indicators of soils with high SOM content included fine texture, dark colour, high plant diversity and presence of macro-organisms.

5.2 Recommendations

Based on the findings, this study proposes the following recommendations.

- ❖ Sustainable Forest Management (SFM) in the Mt Kenya ecosystem is critical in maintaining the region's carbon balance and ensuring the continuous provision of ecosystem goods and services. This can be achieved through strengthening the collaboration among the relevant stakeholders, key among them forest communities and the county government, in preventing forest encroachment for agricultural purposes, illegal logging, forest fires, and illegal grazing, among other threats to the forest. Rehabilitation of the degraded forest areas using native indigenous species is also vital for restoring the forests' ecosystem goods and services.
- ❖ RSMPs adoption should be promoted among smallholder farmers to curb SOM loss via erosion. This can be achieved by providing incentives to farmers, especially the youth, to stimulate RSMPs adoption by non-practicing young farmers. Improved access to credit among smallholder farmers can also help provide the much-required capital to initiate and maintain RSMPs. The improved adoption of RSMPs by farmers in the study

area can also enhance the farmland’s SOCS, which will contribute to improved agricultural productivity and general ecosystem sustainability.

- ❖ Promotion of crop residue use, agroforestry systems, manure application, mulching, intercropping, crop rotation, and tied ridges among the farmers as they are the RSMPs which positively influence SOCS in the study area.
- ❖ Ensuring that farmers have long-term, secure leases will encourage them to invest in RSMPs, as they will have confidence that they can reap the benefits of their investment in the long run. Encouraging farmers to form cooperatives or share labour resources can also help mitigate labour shortages.
- ❖ Subsidized access to technology and establishment of community-based technology rental schemes by the government and development partners can help improve the adoption of RSMPs. The use of alternative fodder and energy sources by promoting the cultivation of alternative fodder crops and the use of agroforestry systems that provide both fodder and fuelwood. This will reduce the reliance on crop residues for energy and fodder.
- ❖ Collaborative efforts involving government agencies, research institutions, NGOs, and local communities are essential for implementing effective soil management and climate change mitigation measures in specific land use and elevation contexts.

Further research:

- ➢ Whereas the current research investigated the status of SOCS in the Mount Kenya ecosystem, there is a need for future studies on the long-term impact of LULC changes on SOCS dynamics because of deforestation and conversion of forestland to farmland. This will provide valuable insights into the ecosystem’s resilience and carbon cycling processes in the Mount Kenya East region.
- ➢ Analysing the policy and governance frameworks governing land use, natural resource management, and agricultural extension services could shed light on the institutional barriers and opportunities for promoting sustainable land management practices and scaling up RSMPs adoption at the regional or national level.

6. NEW SCIENTIFIC RESULTS

For the first time, the quantity of SOCS under different land use types, management practices and soil depths and its trend along an elevation gradient were determined in the Mount Kenya east region. It was established that:

1. SOCS varied between land use types. SOCS recorded in the forestland was about three times more than the farmland SOCS. Variations of SOCS within individual land use types were also noted. This finding underscores the detrimental impacts of LULC changes and human disturbance on SOCS in any given landscape.
2. SOCS generally decreased with increasing soil depth across both land use types, with significant differences being recorded between the topsoil and subsoil SOCS in the forestland.
3. There was an increase in SOCS with elevation in the order of lower farmland<middle farmland<upper farmland<lower forestland<middle forestland<upper forestland, indicating the importance of elevation gradient in influencing soil health and carbon storage through its influence on environmental and soil forming factors.
4. A survey of smallholder farmers revealed that farm size, agroecological zonation, distance from homestead to farms, and the HH age influenced RSMPs adoption.
5. Crop residue management, agroforestry, manure application, mulching, intercropping, crop rotation, and tied ridges RSMPs had significant impacts on SOCS on the eastern slopes of Mount Kenya.

SUMMARY

SOC is vital for food production and climate change mitigation due to its influence on soil fertility, soil health, and soil quality. Understanding the influence of land use, elevation and management practices on SOC is principal in formulating strategies for climate change mitigation and improving agricultural productivity globally. The eastern slope of Mount Kenya was deliberately selected for this study because of its favourable agricultural soils, conducive climatic conditions, and great variations in elevation within short distances. This unique altitudinal gradient leads to a varied range of ecosystems within a relatively small area that plays a vital role in the provision of ecosystem services, carbon sequestration, supporting agricultural activities, and sustaining the livelihoods of smallholder farmers. Knowledge of the influence of land use and elevation gradient on SOCS and the adoption of RSMPs in the region is therefore essential for effective land management, sustainable agricultural practices, and mitigation of the impacts of climate change.

The first part of the research explored how land use types and elevation gradients influence SOCS on the eastern slopes of Mount Kenya. Using a stratified systematic sampling approach, 68 soil samples were collected from two depths of 0–20 and 20–40 cm, representing forestland and farmland. The sampling was carried out across six elevation gradients ranging from 1000 to 2650 m. The collected soil samples were then analysed for bulk density (BD), pH, soil texture, Soil Organic Carbon concentration (SOC), and Total Nitrogen concentration (TN) using standard methods. Statistical analysis was subsequently conducted using R software and Microsoft Office Excel 2016. The mean SOCS in the forestland was significantly higher (111.11 ± 30.49 Mg ha^{-1}) compared to the farmland (36.02 ± 9.54 Mg ha^{-1}). The SOCS generally exhibited a declining trend with increasing soil depth in both land use types. Based on the elevation gradient, the mean SOCS in the aggregated 0–40cm depth ranged from 29.21 ± 5.6 Mg ha^{-1} in the lower farmland (1000–1200 m) to 141.75 ± 17.4 Mg ha^{-1} in the upper forestland (2350–2650 m). There was a notable increasing trend in the SOCS values with an increase in elevation in the order of lower farmland<middle farmland<upper farmland<lower forestland<middle forestland<upper forestland.

The second part of the study investigated the types, determinants, and challenges of the adoption of RSMPs among smallholder farmers in Mount Kenya east region for enhanced SOCS and reduced SOM losses. Primary data was collected from three administrative wards of Tharaka Nithi County (TNC) in Eastern Mount Kenya using a household (HH) questionnaire, Key Informant Interviews (KII), and field observations. R version 4.3.3, STATA

version 18 and Microsoft Office Excel 2016 software were used to analyse the HH survey data, using descriptive statistics, inferential statistics, and the binary logistic regression model. The study findings showed that 65.33% of the respondents adopted RSMPs on their farms, while 34.67% did not at the time of the study. The study findings further revealed that farm size (β= 0.641; $p<0.05$) and agroecological zonation (AEZ) (β= 1.341; $p<0.05$) positively contributed to the adoption of RSMPs. Conversely, the distance from homestead to farms (β= -0.003; $p<0.05$) and the age of the HH heads (β= -0.039; $p\leq0.05$) negatively influenced the adoption of RSMPs among the farmers. Challenges in RSMPs implementation included financial constraints (76.53%), inadequate labour (62.24%), competing uses (41.83%), lack of technology (34.69%), environmental constraints (17.35%), and farm factors (14.29%).

The third part of the study sought to ascertain the influence of RSMPs on the SOCS in the study area and find out farmers' SOM knowledge and perceived benefits. The ANOVA results showed crop residue management and agroforestry had a highly positive significant effect on SOCS ($p<0.001$) while manure application, mulching, intercropping, crop rotation, and tied ridges had a significant positive influence on SOCS ($p<0.05$) on the eastern slopes of Mount Kenya. Regarding farmers SOC and SOM knowledge, none of the farmers was aware of SOC whereas about 77% were knowledgeable about SOM. They listed fine soil texture (63.48%), black colour (59.13%), high plant diversity (52.17%), and a high number of soil macro-organisms (27.83%) as the key indicators of soils with high OM content. The perceived benefits of high SOM content included high crop yields (97.39%), soil erosion control (66.96%), improved soil structure (65.22%), and climate change mitigation (23.48%).

The findings of this study emphasize the substantial impact of land use, elevation and management practices on SOCS, highlighting the crucial role of the Mt Kenya forest in maintaining high levels of SOCS, which is central for soil health and climate change mitigation. It also shows the potential of the farmlands in the study area for carbon sequestration if the RSMPs with significant influence on SOCS are embraced by the farmers. The results also provide baseline data for monitoring soil health in the Mount Kenya ecosystem. It serves as a basis for future assessments and sustainable management strategies to promote soil health and enhance climate change mitigation measures. The study findings further hold the potential to guide the TNC government in formulating tailored strategies that can foster the adoption and sustainable implementation of RSMPs among smallholder farmers. If properly implemented, the strategies will bolster agricultural productivity, mitigate soil erosion, and enhance the region's overall environmental and economic well-being.

APPENDICES

A1: Bibliography

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A2: Household questionnaire

Introduction

This questionnaire survey seeks to collect data on farm management practices for purposes of PhD research titled '***Soil organic carbon stock dynamics as influenced by land use, elevation and management practices on the eastern slopes of Mount Kenya***'. The information collected shall be treated with utmost confidentiality and will not be disclosed to a third party unless where consent is sought and granted.

I would be glad if you would help in responding to the questions in this questionnaire.

Start time………………. Date……………… Coordinates……………….

Surveyor…………………. Photo of farm……………. Ward………………….

A. **Demographic and socio-economic characteristics**

1. a) Gender	b) Age (years)	c) Level of education	d) Occupation	e) No. of HH Members
Male ☐ Female ☐	……………..	None ☐ Primary ☐ Secondary ☐ Tertiary ☐	………………	……………….
f) Marital status Single ☐ Married ☐ Divorced ☐ Widowed ☐ Separated ☐	f) Mean Monthly Income (KES) <5000 ☐ 6000-20000 ☐ 21000-35000 ☐ 36000-50000 ☐ >50000 ☐			

B. **Farm characteristics**

2. Size of the farm in acres............
3. Distance of farm from homestead (m)…………
4. Farm slope

   Flat ☐ Gently sloping ☐ Steep ☐ Very steep ☐

5. Land ownership A. Private ☐ B. Community ☐ Leased ☐ C. State ☐
6. For how long have you been in farming?

   A <5 Years B. 5-10 Years C. 11-15 Years D. 16-20 Years E. >20 Years
7. What was the previous land use/cover before farming?

   A. Forest land ☐ B. Grassland ☐ C. Bareland ☐ D. Wetland ☐ E. Shrubla ☐

   F. Other……………...(specify)
8. What type of farming are you engaged in?

   A. Crop farming ☐ B. Livestock farming ☐ C. Mixed farming ☐
9. Reason for farming A. Subsistence ☐ B. Commercial ☐ C. Both ☐
10. Which crops do you grow on your farm and during which rainy season? (*Use Table 1 to respond to questions 8, If NA skip to question 9*)

Table 1: Crops grown and seasons of cultivation *(Respondents can select more than one response as applicable)*

Crops grown			
Maize			
Rice			
Tea			
Coffee			
Vegetables			
Legumes			
Potatoes			
Fruit crops			
Sugarcane			
Bananas			
Pasture			
Beans			
Other (specify)….			

11. What cropping system do you practice on your farm?

A. Monocropping ☐ B. mixed cropping ☐ C. Agroforestry ☐

D. Other……………. (specify)

12. Which type of livestock do you keep on your farm? (*Use Table 2 to respond to questions 10, If NA skip to question 11)*

Table 2: Livestock data *(Respondents can select more than one response as applicable)*

Livestock	Approximate Number
Exotic dairy cattle	
Indigenous dairy cattle	
Beef cattle	
Goats	
Sheep	
Poultry	
Fish farming	
Other (Specify)………………………	
Total livestock unit	

C. **Farm management practices**

Land preparation methods

13. Which of the following land preparation methods do you practice on your farm (*you can select more than one, as applicable)*

Table 3. land preparation practices

Land preparation method	YES	NO
Minimum tillage		
Hand cultivation		
Ox-plough		
Tractor		
Other (specify)………………		

Fertilizers use on the farm

14. Do you use fertilizer on your farm? A. YES ☐ B. NO ☐

15. What type of fertilizer do you use in your farm? (*If NA skip to the next question*)

A. Organic ☐ B. Inorganic ☐ C. Both ☐

16. Table 5. Inorganic fertilizer use (*If NA skip to the next question)*

Activity	Choices
a. Do you use inorganic fertilizer during planting	YES ☐ NO ☐
b. Which brand of fertilizer do you use during planting	
c. What is the application rate/acre?	
d. Do you top-dress your crops with inorganic fertilizers?	YES ☐ NO ☐
e. If yes, which brand of fertilizer do you use for top dressing?	
f. What is the application rate/ acre?	

Inorganic fertilizer/Manure

17. Do you use manure on your farm? 1. Yes ☐ 0. No ☐ (*If NA skip to the next question).*
18. What type of manure?
19. What is the source of manure?
20. What quantity of manure (kgs) do you apply in your farm?

(Use Table 6 for questions 19 -21. You can indicate more than one, as applicable)

Table 6. Types and sources of manure *(Respondents can select more than one response as applicable)*

Type of manure	0=No, 1=Yes	Source	Quantity (kg)
Farmyard manure			
Poultry manure			
Biogas slurry			
Green manure			
Compost manure			
Goat manure			
Cattle manure			

Type of manure	0=No, 1=Yes	Source	Quantity (kg)
Other(specify)……………			
Sources: 1. Own farm 2. Free From neighbour 3. Purchase from neighbour 4. Purchase from next village 5. Purchase from market centre 6. Others (specify)……			

Post-harvest management practices

21. How do you manage crop residues after harvesting your crop? *(You can choose more than one, as applicable)*

A. Burning ☐ B. Composted ☐ C. incorporated in situ ☐

D. Used as fodder ☐ E. Used for fuel ☐ F. Sold ☐

22. How long do you leave your farm fallow after harvesting crops?

A. I plough it immediately ☐ B. less than one month ☐ C. 1-4 months ☐
D.5-6 months ☐ E. > 7 months

Recommended management practices

23. Do you experience soil erosion on your farm?

1. Yes ☐ 0. No ☐

24. Do you carry out RM in your farm?

1. Yes ☐ 0. No ☐

25. If yes, which of the below RSMPs do you carry out in your farm *(You can choose more than one, as applicable)*

A. Contour farming ☐ B. Conservation tillage ☐ C. Strip cropping ☐
D. Terracing ☐ E. Crop rotation ☐ F. Mulching ☐ G. Cover crops ☐
H. Agroforestry ☐ I. Others……………. (specify)

26. Do the RSMPs help enhance SOCS and reduce soil erosion?

1. Yes ☐ 0. No ☐

27. What challenges do you face in the adoption and maintenance of the RSMPs?

A. Financial constraints ☐
B. Inadequate Labour ☐

C. Competing uses ☐

D. Lack of technology ☐

E. Environmental constraints ☐

F. Farm factors ☐

28. What is the source of labour for your farm?

A. Family ☐ B. Hired ☐ C. Both ☐

29. Do you access credit facilities to boost your farming practices?

1. Yes ☐ 0. No ☐

29. a) Do you know what SOC/SOM is?

1. Yes ☐ 0. No ☐

b) What are the indicators of soils with high Soil organic matter content? *(if answer in 38 is yes)*

A. Dark colour ☐ B. Good texture ☐ C. High macroorganisms ☐

D. High plant diversity ☐

30. What are the benefits of soil organic matter?

A. High crop yields ☐ B. Climate change mitigation ☐

C. Controls soil erosion ☐ D. Improves soil structure ☐

*****THE END*****

A3: Key informants' questionnaire

This interview seeks to collect data on farm management practices for purposes of a PhD research. The information collected will strictly be used for accomplishing the stated academic objective and shall be treated with utmost confidentiality and will not be disclosed to a third party unless where consent is sought and granted.

Recommended farm management practices (RSMPs)

1. What are the most common RSMPs practiced by farmers in this region?
2. Can you identify any patterns in the adoption of these practices?

Adoption of RSMPs

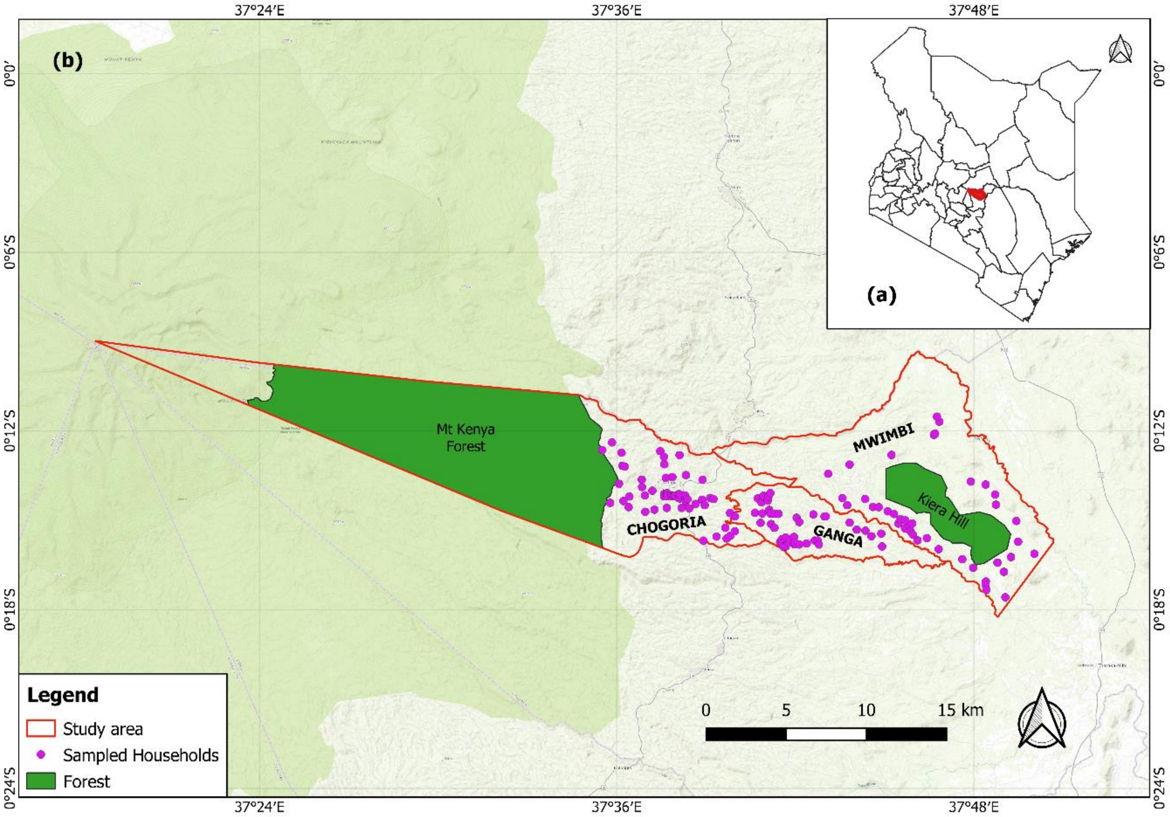
3. What percentage of farmers in this region have adopted the RSMPs?
4. Which specific RSMPs are most commonly adopted by farmers, and why?
5. How do farmers perceive the benefits and risks of adopting RSMPs?
6. What role do extension services play in influencing adoption of RSMPs?
7. How do you disseminate information on the adoption of RSMPs to the farmers?
8. What methods of information dissemination are most effective?

Challenges facing RSMPs adoption

9. What are the main challenges that farmers face in the adoption of RSMPs?
10. What types of support are available to farmers to help them adopt RSMPs?
11. How do local institutions contribute to promoting adoption, and how effective are their interventions?
12. Are there any institutional challenges that hinder the adoption of RSMPs?
13. In your opinion, what measures can be taken to improve farmers' adoption of RSMPs?

****THE END****

A4: Sampled households' distribution in the study area



A5: Location, land use, and elevations of the sampled sites

SITE CODE	LATITUDE	LONGITUDE	LAND USE	ELEVATION
FL01	-0.18485	37.46660	Forestland	2650
FL02	-0.18967	37.47383	Forestland	2600
FL03	-0.19238	37.47962	Forestland	2550
FL04	-0.19720	37.48454	Forestland	2500
FL05	-0.20125	37.49120	Forestland	2450
FL06	-0.20723	37.49969	Forestland	2400
FL07	-0.21601	37.50943	Forestland	2350
FL08	-0.21987	37.51831	Forestland	2300
FL09	-0.22585	37.52390	Forestland	2250
FL10	-0.22807	37.52882	Forestland	2200
FL11	-0.23155	37.53162	Forestland	2150
FL12	-0.23405	37.54040	Forestland	2100
FL13	-0.23647	37.54638	Forestland	2050
FL14	-0.23492	37.55304	Forestland	2000
FL15	-0.23637	37.56085	Forestland	1950
FL16	-0.23637	37.56741	Forestland	1900
FL17	-0.23917	37.57330	Forestland	1850
FL18	-0.23724	37.58459	Forestland	1800
FL19	-0.24052	37.59153	Forestland	1750
CL01	-0.24023	37.59636	Farmland	1700
CL02	-0.24129	37.60736	Farmland	1650
CL03	-0.24418	37.62163	Farmland	1600
CL04	-0.24293	37.62800	Farmland	1550
CL05	-0.24245	37.63485	Farmland	1500
CL06	-0.24332	37.64141	Farmland	1450
CL07	-0.24573	37.66293	Farmland	1400
CL08	-0.24486	37.67730	Farmland	1350
CL09	-0.24611	37.69062	Farmland	1300
CL10	-0.24602	37.70277	Farmland	1250
CL11	-0.24781	37.71659	Farmland	1200
CL12	-0.24920	37.73297	Farmland	1150
CL13	-0.25026	37.74889	Farmland	1100
CL14	-0.25007	37.75689	Farmland	1050
CL15	-0.25113	37.76625	Farmland	1000

A6: Forestland soil physicochemical properties

SITE_ID	DEPTH (cm)	BD (g cm^{-3})	SOC (%)	SOCS (Mg ha^{-1})	pH	SOIL TEMP.	TN (%)	C:N	SAND (%)	SILT (%)	CLAY (%)
FL01	0_20	0.44	13.65	119.22	5.7	14	1.25	10.92	68.06	28.24	3.70
FL01	20_40	0.54	10.50	114.13	6.0	15	0.73	14.38	39.62	52.05	8.33
FL02	0_20	0.45	17.11	154.87	5.2	15	1.28	13.37	85.33	13.03	1.64
FL02	20_40	0.49	12.67	124.65	5.6	14	0.90	14.08	65.51	30.07	4.42
FL03	0_20	0.52	16.35	168.75	5.3	15	1.54	10.62	74.92	22.84	2.24
FL03	20_40	0.56	11.95	132.80	5.1	15	1.12	10.67	59.60	35.32	5.08
FL04	0_20	0.45	16.41	148.30	4.7	15	1.31	12.53	46.37	46.73	6.89
FL04	20_40	0.54	12.74	136.45	4.9	14	0.95	13.41	44.10	47.09	8.82
FL05	0_20	0.47	17.43	165.26	4.4	15	1.40	12.45	45.85	47.68	6.48
FL05	20_40	0.53	14.02	148.58	4.5	15	1.00	14.02	42.28	48.43	9.29
FL06	0_20	0.56	13.47	151.23	4.8	15	0.76	17.72	32.88	56.65	10.47
FL06	20_40	0.67	10.23	136.76	4.9	14	0.95	10.77	27.14	61.49	11.37
FL07	0_20	0.71	8.07	113.82	5.0	15	0.63	12.81	34.99	53.92	11.09
FL07	20_40	0.71	7.67	108.367	4.7	13	0.68	11.28	22.40	61.66	15.94
FL08	0_20	0.53	10.39	111.11	4.6	15	0.89	11.67	47.25	41.34	11.41
FL08	20_40	0.73	6.24	90.90	4.4	15	0.52	12.00	21.72	53.11	25.18
FL09	0_20	0.65	9.50	123.05	4.4	15	0.80	11.88	32.96	55.15	11.88
FL09	20_40	0.79	6.11	96.91	4.4	14.5	0.50	12.22	16.34	53.47	30.18
FL10	0_20	0.62	7.59	94.82	4.2	15	0.67	11.33	27.50	55.59	16.91
FL10	20_40	0.68	4.93	67.11	4.4	15	0.42	11.74	11.74	57.83	30.43
FL11	0_20	0.58	12.26	142.47	3.9	15	1.00	12.26	43.31	45.49	11.20
FL11	20_40	0.61	7.24	87.94	3.8	14	0.54	13.41	21.13	53.19	25.67
FL12	0_20	0.64	9.38	120.05	4.0	16	0.74	12.68	31.74	53.97	14.29
FL12	20_40	0.79	5.92	93.83	4.1	15	0.45	13.16	10.80	61.98	27.21
FL13	0_20	0.64	7.99	102.89	3.9	17	0.71	11.25	28.49	55.42	16.10
FL13	20_40	0.79	5.05	80.08	4.0	16	0.43	11.74	11.53	56.74	31.73
FL14	0_20	0.68	6.75	91.94	4.2	17	0.59	11.44	24.56	57.3	18.14
FL14	20_40	0.71	2.70	38.31	4.5	16	0.23	11.74	5.82	59.76	34.42
FL15	0_20	0.66	10.98	144.73	3.7	16	0.88	12.48	32.97	53.38	13.65
FL15	20_40	0.68	5.63	77.09	4.0	15	0.42	13.40	10.40	55.77	33.83
FL16	0_20	0.59	11.12	131.65	3.9	16	0.84	13.24	32.17	53.03	14.80
FL16	20_40	0.77	6.22	96.12	4.2	16	0.5	12.44	14.68	57.19	28.13
FL17	0_20	0.78	6.14	96.02	4.2	16	0.5	12.28	22.45	53.99	23.56
FL17	20_40	0.74	4.59	67.84	4.4	17	0.37	12.41	10.21	52.74	37.06
FL18	0_20	0.73	7.13	103.94	4.2	17	0.64	11.14	20.15	57.22	22.63
FL18	20_40	0.81	5.33	85.856	4.3	17	0.45	11.84	14.41	53.33	32.26
FL19	0_20	0.77	5.67	87.40	4.3	17	0.43	13.19	17.55	57.58	24.86
FL19	20_40	0.80	4.16	66.96	4.3	17	0.30	13.87	5.45	57.24	37.31

A7: Farmland soil physicochemical properties

SITE_ID	DEPTH (cm)	BD (g cm^{-3})	SOC (%)	SOCS (Mg ha^{-1})	pH	SOIL TEMP	TN (%)	C:N	SAND (%)	SILT (%)	CLAY (%)
CL01	0_20	0.66	2.60	34.31	4.9	23	0.25	10.40	13.58	46.41	40.02
CL01	20_40	0.74	2.33	34.71	4.9	21	0.23	10.13	12.74	44.43	42.83
CL02	0_20	0.68	3.41	46.32	5.3	24	0.26	13.12	11.36	51.14	37.50
CL02	20_40	0.83	2.90	48.25	5.2	19	0.21	13.81	9.79	45.25	44.97
CL03	0_20	0.66	3.77	49.71	4.7	25	0.30	12.57	9.85	59.47	30.68
CL03	20_40	0.78	3.16	49.11	4.5	22	0.24	13.17	12.95	52.35	34.69
CL04	0_20	0.76	2.96	44.87	5.4	22	0.27	10.96	16.75	49.04	34.21
CL04	20_40	0.85	2.92	49.84	5.6	21	0.27	10.81	14.84	49.49	35.67
CL05	0_20	0.89	2.75	48. 80	5.9	18	0.26	10.58	13.00	46.58	40.42
CL05	20_40	0.98	1.85	36.25	6.0	17	0.18	10.28	10.49	39.00	50.51
CL06	0_20	0.86	2.60	44.81	5.4	21	0.23	11.30	15.81	45.37	38.82
CL06	20_40	0.82	2.10	34.51	5.2	21	0.19	11.05	11.84	47.63	40.53
CL07	0_20	0.84	2.17	36.38	5.5	26	0.21	10.33	36.68	31.16	32.16
CL07	20_40	0.98	1.64	32.01	5.4	24.5	0.17	9.65	7.38	45.20	47.42
CL08	0_20	0.82	2.48	40.72	5.1	21	0.24	10.33	21.50	44.58	33.92
CL08	20_40	0.81	1.59	25.85	4.9	20	0.16	9.94	11.58	44.18	44.24
CL09	0_20	0.89	2.80	50.38	5.6	25	0.27	10.37	20.01	45.20	34.80
CL09	20_40	0.91	2.00	36.34	6.0	23	0.20	10.00	11.53	46.00	42.48
CL10	0_20	0.91	1.55	28.19	5.9	27	0.16	9.69	14.71	39.61	45.67
CL10	20_40	0.97	0.89	17.27	5.8	25.5	0.12	7.42	6.47	38.96	54.57
CL11	0_20	0.88	1.23	21.86	5.7	25	0.14	8.79	18.01	40.97	41.02
CL11	20_40	0.89	1.06	19.00	5.7	24	0.12	8.83	19.43	39.75	40.81
CL12	0_20	0.96	1.93	37.00	5.7	27	0.17	11.35	34.91	34.96	30.13
CL12	20_40	1.01	1.53	31.01	5.7	26	0.14	10.93	14.98	45.20	39.82
CL13	0_20	0.98	1.69	33.28	5.8	27	0.16	10.56	23.19	40.58	36.23
CL13	20_40	1.10	1.29	28.40	5.8	26	0.13	9.92	12.71	45.74	41.55
CL14	0_20	0.96	1.69	32.51	5.8	25	0.15	11.27	30.92	34.97	34.10
CL14	20_40	1.01	1.44	29.20	5.9	24.5	0.13	11.08	17.90	41.78	40.32
CL15	0_20	0.93	1.82	33.82	5.8	24	0.16	11.38	17.75	40.92	41.33
CL15	20_40	1.11	1.17	25.98	5.9	23	0.11	10.64	12.59	38.94	48.46

A8: Soil pH interpretation

pH	**Rating**
<4.5	Extremely acid
4.5-5.0	Very strongly acid
5.1-5.5	Strongly acid
5.6-6.0	Medium acid
6.1-6.5	Slightly acid
6.6-7.3	Neutral
7.4-7.8	Mildly alkaline
7.9-8.4	Moderately alkaline
8.5-9.0	Strongly alkaline
>9.0	Very strongly alkaline

(Source: Wanjogu et al, 2001)

A9: SOC ratings

pH	**Rating**
>6.0	Very high
4.3-6.0	High
2.1-4.2	Medium
1.0-2.0	Low
<1.0	Slightly acid

A10: NACOSTI research license

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Ref No: **979339**

Date of Issue: **01/October/2022**

RESEARCH LICENSE

This is to Certify that Mr.. Brian Rotich Kanyongi of Hungarian University of Agriculture and Life Sciences, has been licensed to conduct research in Embu, Meru, Tharaka-Nithi on the topic: Investigation of the spatial distribution of soil organic carbon in the eastern slopes of Mount Kenya: A case study for the Soils4Africa project for the period ending : 01/October/2023.

License No: **NACOSTI/P/21/13179**

979339

Applicant Identification Number

Director General
NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Verification QR Code

NOTE: This is a computer generated License. To verify the authenticity of this document, Scan the QR Code using QR scanner application.

A11: Phytosanitary certificate

No. 4809025

KEPHIS CERT 4809025

MINISTRY OF AGRICULTURE, LIVESTOCK AND FISHERIES

KENYA PLANT HEALTH INSPECTORATE SERVICE (KEPHIS)

PHYTOSANITARY CERTIFICATE

Agricultural Produce (Export) Act Cap 319

1. Name and address of exporter Brian Rotich Kanyongi P.O BOX 109- 60400,Chuka Kenya	*2. PHYTOSANITARY CERTIFICATE No.* KEPHIS/4/3321003/2023
3. Declared name and address of consignee Hungarian University of Agriculture and Life Sciences Pater Karoly, U . 1,Godollo,2100 HUNGARY	*4. To Plant Protection Organization(s) of* HUNGARY
5. Place of Origin Kenya	*6. Declared means of conveyance:* By Air
7. Declared point of entry Budapest Ferenc Liszt Airport	*8. Distinguishing marks* Labelled
9. Number and Description of packages: 1 Packages of 18.80 Kgs.	*10. Name of Produce* Soil Sample
11.Botanical name of plants Soil Sample	*12. Quantity declared* 18.80 Kgs

13.This is to certify that the plants, plant products or other regulated articles described herein
Have been inspected and/or tested according to appropriate official procedures and are considered to be free from the quarantine pests specified by the importing country and to conform with the current phytosanitary requirements of the importing country

14. Additional declaration
****

15. Disinfestation and/or disinfection treatment **** *16. Chemical (active ingredient)* **** *17. Duration and temperature* **** *18. concentration* **** — *19. Date* *****	*place of issue* Kephis Headquarters Date 31 Jul 2023 *Name of Inspector* Elijah Mutua *Name of Authorized Officer* Bernard Mukoye *Signature* .... *of Authorized officer*
20. Any additional Information For Research Purposes ONLY.	(Official Stamp) STATE DEPARTMENT OF AGRICULTURE, Kenya Plant Health Inspectorate Service, National Plant Protection Organization, KEPHIS HQS — PASSED 31 JUL 2023

Note: The certificate shall be completed in typescript or in block capitals
No financial liability with respect to this certificate shall attach to Kenya Plant Health Inspectorate Service or to any of its officers or representatives.

A12: Kenya Forest Service research permit

KENYA
Forest Service

Kenya Forest Service Hqs
Karura, Off Kiambu Rd
P.O. Box 30513 - 00100
Nairobi, Kenya

Ref: No. RESEA/1/KFS/VOL. VI/115 ... Date 21st January 2022

Brian Rotich
Faculty of Agricultural and Environmental Sciences,
Hungarian University of Agriculture and Life Sciences,
P´ater K´aroly u. 1, Gödöllő, 2100, Hungary.
kanyongi.brian.rotich@phd.uni-szie.hu

RE: PERMISSION TO CONDUCT RESEARCH IN EMBU, THARAKA-NITHI AND MERU COUNTIES.

Reference is made to your letter of 1st October 2021 requesting access to forests in Embu, Tharaka-Nithi and Meru Counties to conduct research on the "the spatial distribution of soil organic carbon in the eastern slopes of Mount Kenya: A case study for the Soils4Africa project".

Permission is hereby granted for you to access the forests for soils collection.

The following conditions shall apply;

I. No information detrimental or of a confidential manner shall be shared publicly without written permission from Kenya Forest Service.
II. Intellectual property rights arising from the study of the materials will be jointly shared by the Kenya Forest Service and yourself.
III. You shall acknowledge the Kenya Forest Service in all and any publications, patents or presentations involving the use of the information.
IV. You shall indemnify and keep the Kenya Forest Service and the State harmless from any claim, action and damage or cost deriving from or in connection with the use of the information.
V. No commercialization shall take place without clearance from Kenya Forest Service.
VI. Material obtained under this permit may only be transferred to a third party with prior written authorization from Kenya Forest Service.
VII. Notwithstanding this validity period, the conditions above (ii - vii) shall hold throughout the existence of the materials.

Trees for better lives

Tel: (254)020-3754904/5/6, (254)020-2014663, (254)020-2020285, Fax: (254)020-2385374
Email: info@kenyaforestservice.org. Web: www.kenyaforestservice.org

This permit is valid from 21st January 2022 to 20th January 2023. The PIC and MTA are part and parcel of this permit.

By a copy of this permit, the Ecosystem Conservator is hereby instructed to facilitate access.

JULIUS KAMAU, EBS
CHIEF CONSERVATOR OF FORESTS

Copy to: Ecosystem Conservator – Embu, Tharaka-Nithi, Meru

BO/sa