HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

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The Thesis of the 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

BY

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1. BACKGROUND OF THE STUDY AND OBJECTIVES

1.1 Background of the study

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). For accurate estimation of Soil Organic Carbon Stock (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).

The SOCS is governed by factors that influence the build-up and the removal of carbon (Ahmad Dar & Somaiah, 2015). 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, while anthropogenic factors include land use and land use/land cover (LULC) changes (Dobos et al., 2005; Fu et al., 2004; Liu et al., 2011; Wang et al., 2018; Wang et al., 2014; Xin et al., 2016). 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).

1.2 Statement of the Problem

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, 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 Specific Objectives of the Study

Based on the above background and the existing research gaps, the following specific objectives were defined for this study.

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 Recommended Soil Management Practices (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.

2. MATERIALS AND METHODS

2.1 Study area

This study focused on Tharaka Nithi County (TNC), located on the eastern slopes of Mount Kenya in central Kenya (*Figure 1*). 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).

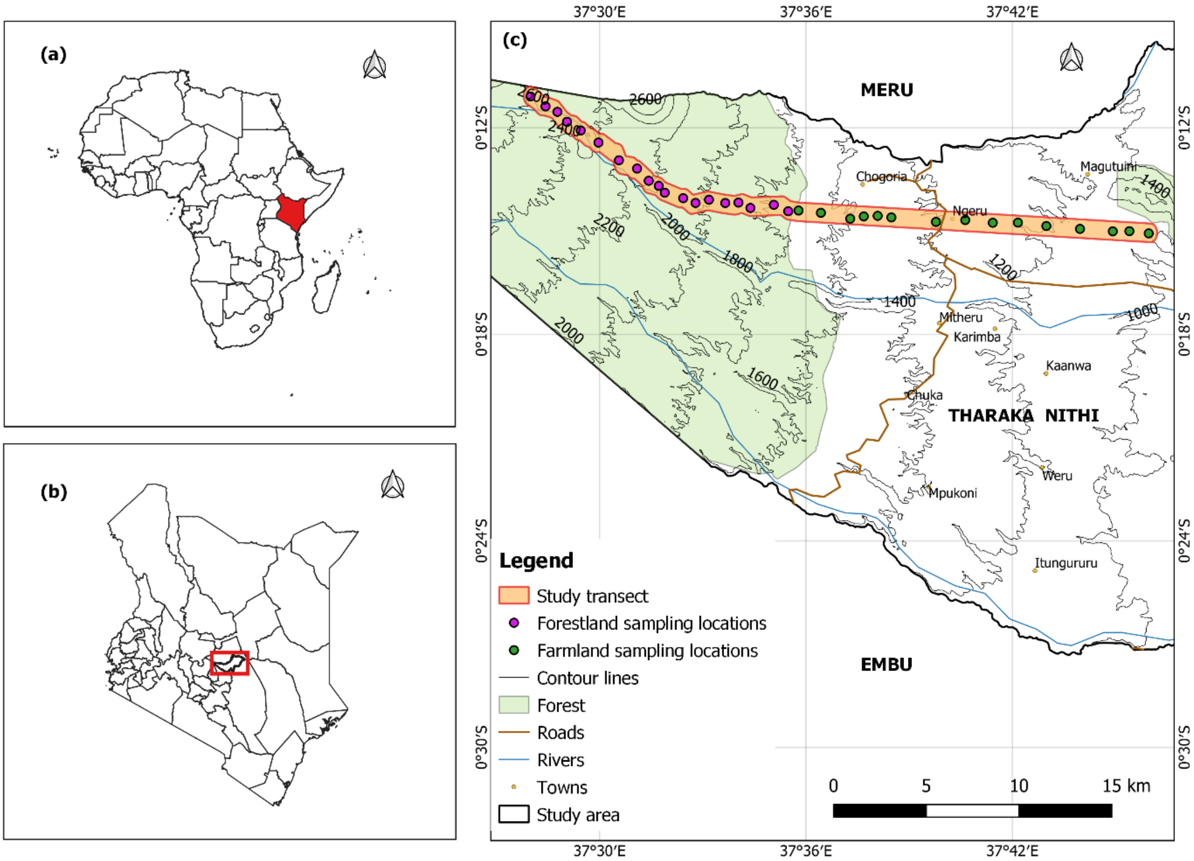


Figure 1: Map of the study area showing (a) The location of Kenya in Africa, (b) The location of the study area in Kenya, (c) The study transect and sampling locations on the eastern slopes of Mount Kenya. (Source: author)

The elevation of TNC ranges from 600 m asl Eastwards in the ASALs of Tharaka to about 5199 m asl at the snowcapped peak of Mount Kenya. The study area's geologic composition mainly comprises volcanic rock, volcanic ash, and some old metamorphic rocks (Schoeman, 1952). The dominant WRB (IUSS Working Group WRB, 2015) Reference soil groups (RSG) in the study area include Nitisols, and Andosols (Dijkshoorn, 2007). Intermediary weathered Humic Andosols are dominant in the forested humid upper slopes (Muchena & Gachene, 1988), while Humic Nitisols dominate the farmlands (Jaetzold et al., 2007).

The study area 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 about 40 °C in the lowlands (County Government of Tharaka Nithi, 2018). The upper slopes of the study area comprise the Mt. Kenya Forest which has a wide range of flora and fauna (Kenya Forest Service, 2010; Kenya Wildlife Service, 2010).

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). 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).

2.2 Soil sampling

2.2.1 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).

2.2.2 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 2*).

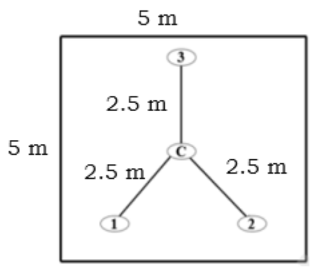


Figure 2: A graphic demonstration of the soil sampling technique used in the study area

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.

2.2.3 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.

2.2.4 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).

2.2.5 Bulk density and SOCS calculations

The soil BD was calculated as per equation (1) (Tadese et al., 2023).

$$\text{BD} = {}^{Ms}/_{Vs} \tag{1}$$

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

SOCS (Mg ha^{-1}) for each depth was then estimated using equation (2) (Mishra et al., 2020).

$$\text{SOCS} = \text{BD} * \text{SOC\%} * \text{D} \tag{2}$$

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

2.2.6 Statistical analysis of soil data

2.2.6.1 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.

2.2.6.2 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 (3). This 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)        (3)
```

2.2.6.3 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 (4).

```
anova_model2 <- aov(SOCS ~ ELEVATION_GRADIENT * DEPTH, data = SOIL)        (4)
```

2.2.6.4 Influence of management practices on SOCS

The additive ANOVA model was also used to assess the influence of the categorical RSMPs on SOCS as per equation (5).

```
anova_model3 <- aov(SOCS ~ Terraces + Agroforestry + Manure…, data = FARM)        (5)
```

2.2.6.5 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.

2.3 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.

2.3.1 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. 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 (6) (Israel, 1992).

$$n = \frac{N}{1+N(e^2)} \tag{6}$$

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

Therefore,

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

$$n = 150.19 \approx 150$$

2.3.2 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. 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 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 also 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).

2.3.3 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 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).

Expressing the binary logistic regression model depicting the HH determinants of adopting RSMPs in stochastic form, the model is presented in equation (7).

$$Y_i = \ln\left(\frac{\mathrm{P}\,\pi_i}{1 - \mathrm{P}\,\pi_i}\right) = \beta_0 + \beta_1 X_1 + \beta_1 X_1 + \cdots \beta_k X_k + \beta_d D_d + \mu_i \quad (7)$$

Where Y_i is the binary outcome variable of interest (adoption of RSMPs), P π_i is the probability of adopting RSMPs and $1 - \text{P}\,\pi_i$, is the probability of not adopting RSMPs, β_0 denotes the intercept, $\beta_1, \ldots, \beta_k$ 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 $i = 1, \ldots, 150$.

A correlation analysis was conducted to determine the degree of association between the household covariates and the adoption of RSMPs (Miles, 2014; Studenmund, 2014). A Variance Inflation Factor (VIF) analysis was also conducted in STATA (version 18) to assess multicollinearity among the explanatory variables (Gujarati, 2003). A summary of the study variables is depicted in *Table 1*.

Table 1: 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*

3. RESULTS AND DISCUSSION

3.1 Soil properties under different land use types and soil depths

3.1.1 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 2*.

Table 2: 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 ($g\ cm^{-3}$)	0–20	0.44	0.78	0.60 ± 0.11bB	0.66	0.99	0.85 ± 0.11aA
	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. (°C)	0–20	14	17	15.58 ± 0.90bA	18	27	24 ± 2.59aA
	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 2)*. 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 2)*. 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., 2022; 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.

3.1.2 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 3)*. The Tukey HSD test further revealed significant mean differences in SOC and SOCS between the two land use types and soil depths.

Table 3: 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 2)*. SOC was significantly higher in the forestland than in the farmland for both depths (*Figure 3*).

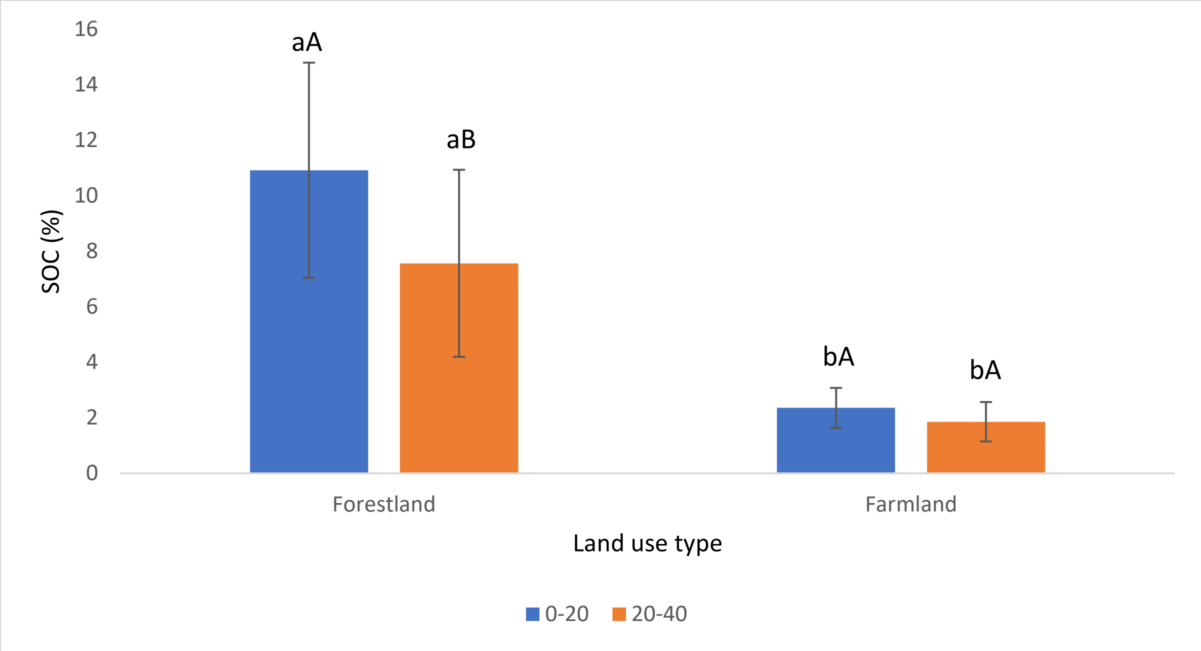


Figure 3: SOC at 0–20 and 20–40 cm depths by land use type in the study sites

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, 2004; 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 4*). 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 4)*.

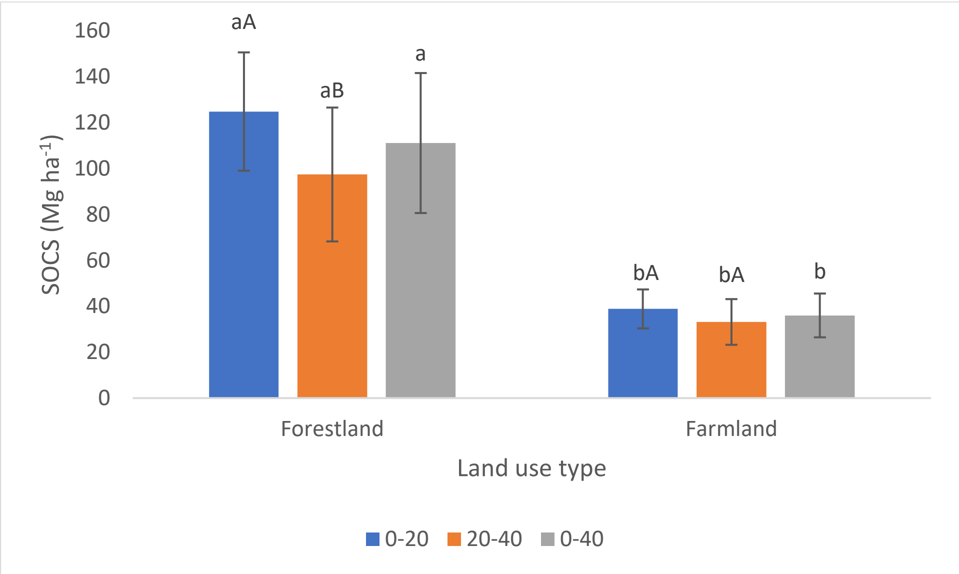


Figure 4: SOCS at 0–20, 20–40, 0–40 cm depths by land use type in the study sites

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, 2007). 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.

3.1.3 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.

3.1.3.1 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 5)*.

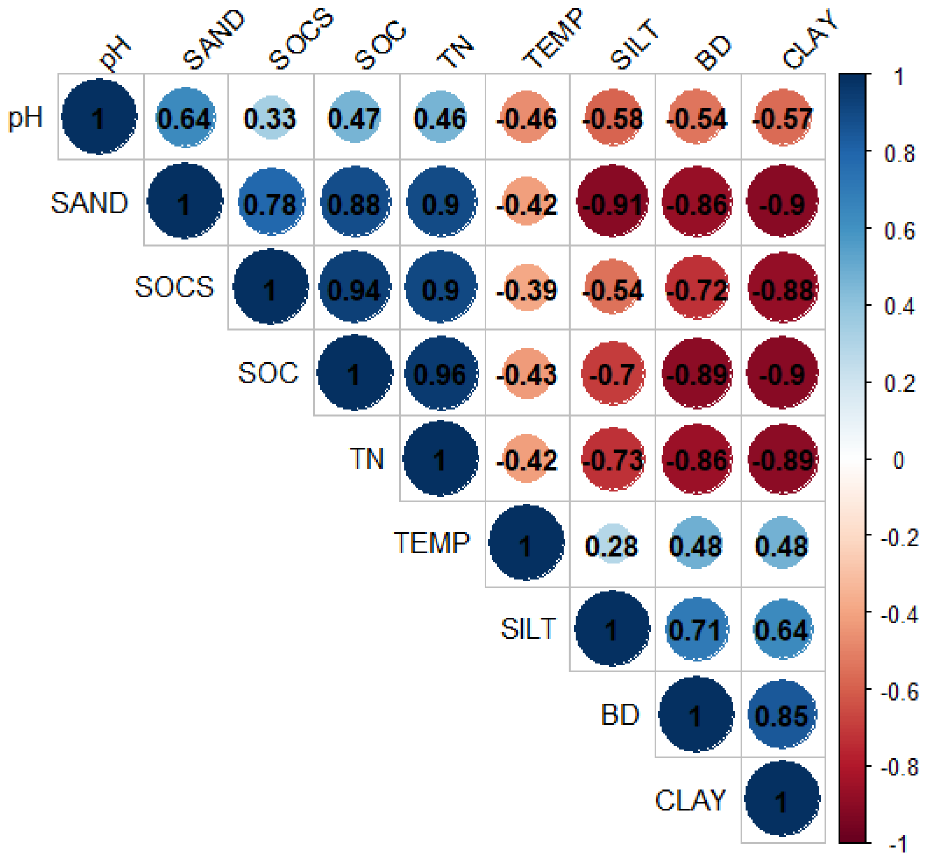


Figure 5: Correlation plot showing the relationship among forestland soil properties

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.*

3.1.3.2 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 fairly 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 6)*.

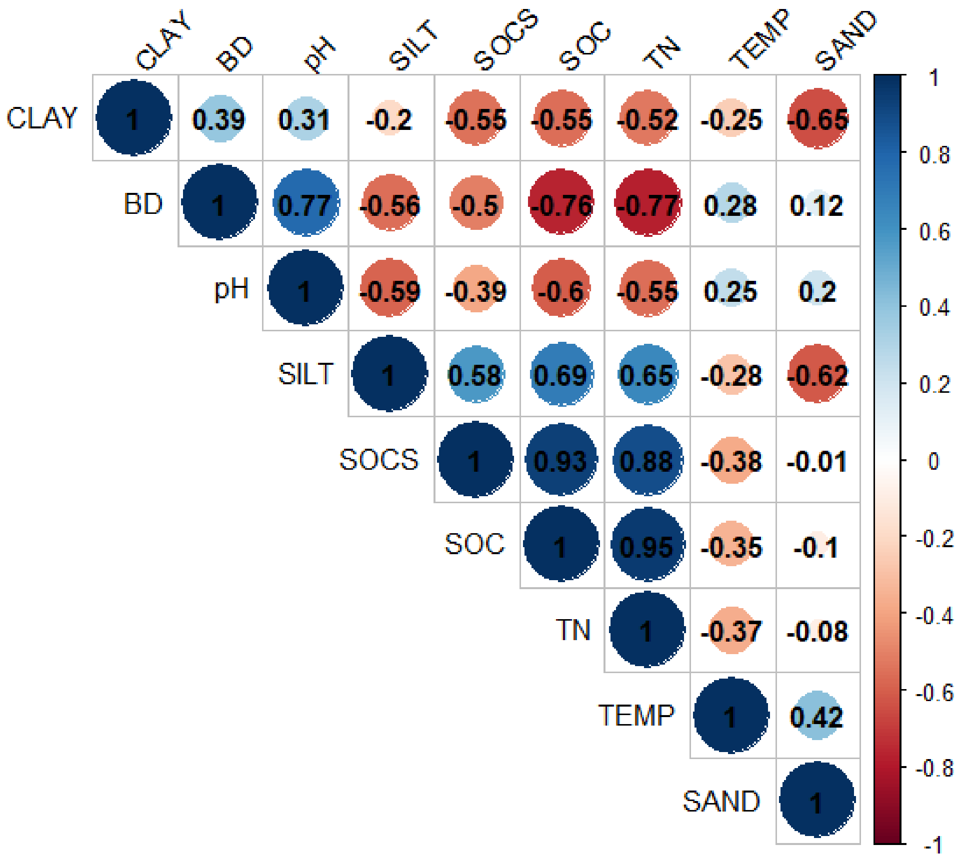


Figure 6: Correlation plot showing the relationship among farmland soil properties

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

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).

3.2 Variation of soil properties along the elevation gradient

3.2.1 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 4.* 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 4)*. 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 4)*. 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 4)*. 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 4).* 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 4)*.

Table 4: 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

3.2.2 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 5*)*.

Table 5: 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 7)*. SOC generally decreased down the elevation gradient and soil depth *(Figure 7)*.

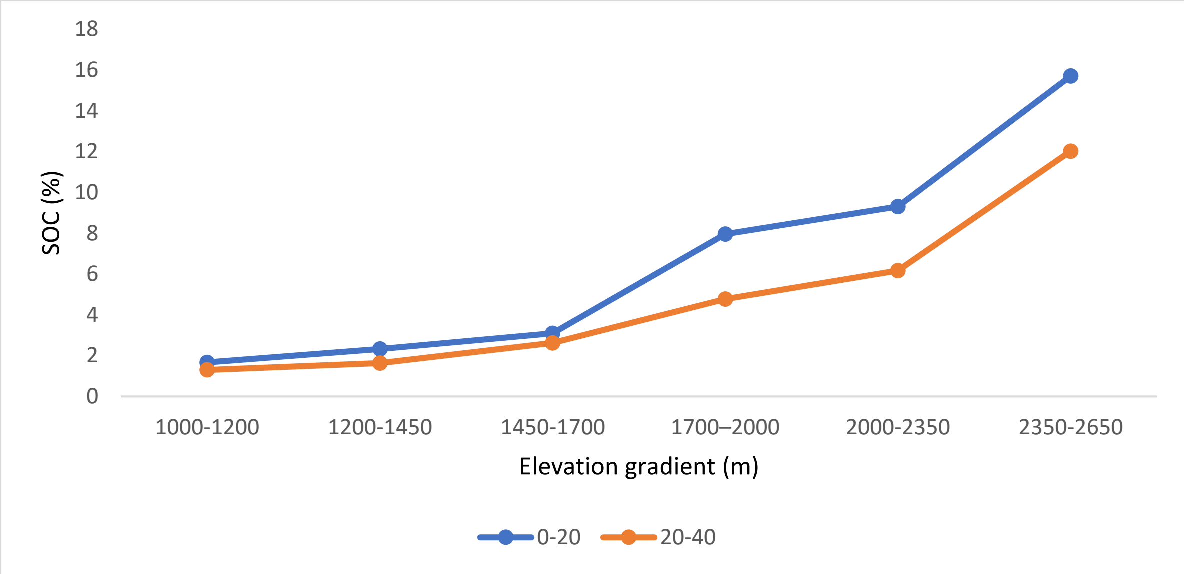
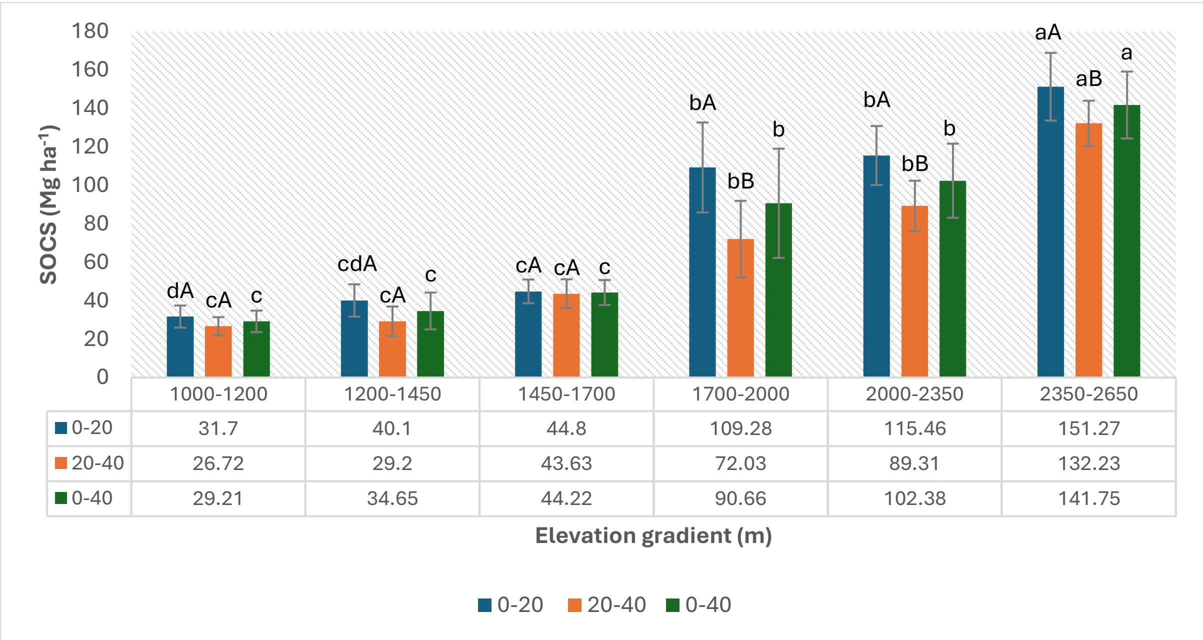


Figure 7: SOC at 0–20 and 20–40 cm depths based on elevation gradient in the study area

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 8)*. 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 8)*. Overall, the SOCS showed an increasing trend with increase in elevation and a decreasing trend with incremental soil depths.



	1000-1200	1200-1450	1450-1700	1700-2000	2000-2350	2350-2650
0-20	31.7	40.1	44.8	109.28	115.46	151.27
20-40	26.72	29.2	43.63	72.03	89.31	132.23
0-40	29.21	34.65	44.22	90.66	102.38	141.75

Figure 8: 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).

3.3 Farmers adoption of RSMPs

3.3.1 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 6)*. 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 6)*.

Table 6: 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.

3.3.2 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. A total of fifteen distinct RSMPs were documented in the study area *(Figure 9)*. 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%).

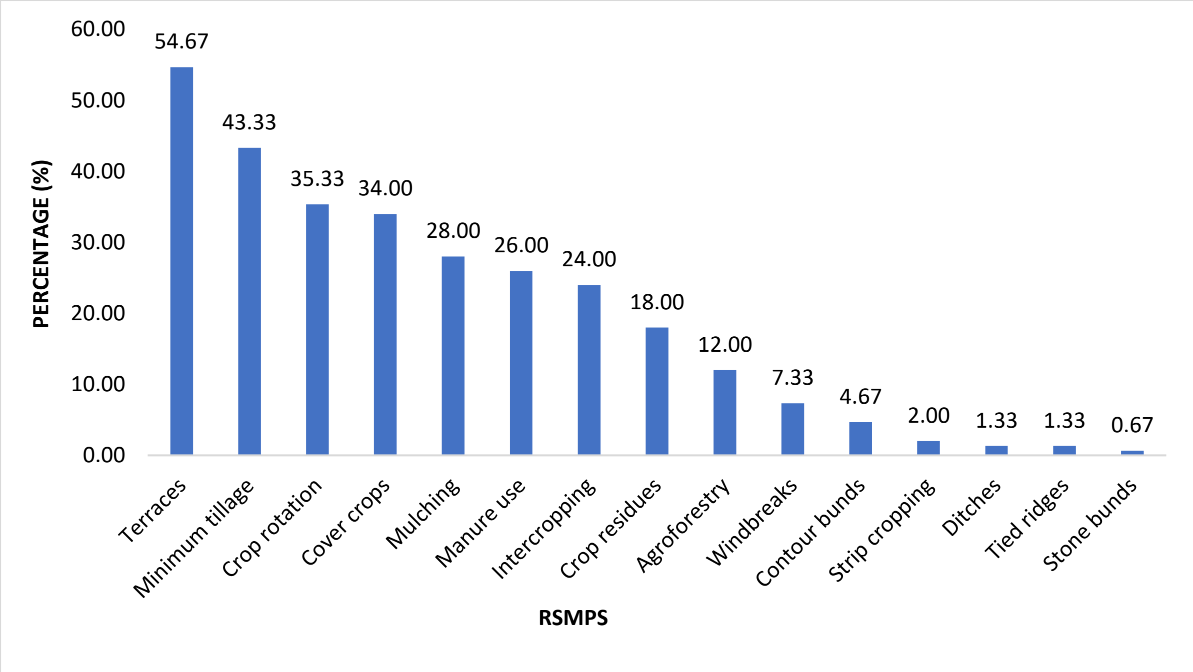


Figure 9: Types of RSMPs in the study area

From the results *(Figure 9)*, 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 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).

3.3.3 Determinants of RSMPs adoption

The findings of the predicted binary logistic regression model coefficient estimates, marginal effect, standard error, and the associated significance values are shown in *Table 7*. 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 7: 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 7)* 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).

3.3.4 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 10*). The top three challenges encompassed financial constraints (76.53%), Inadequate labour (62.24%), and competing uses (41.83%).

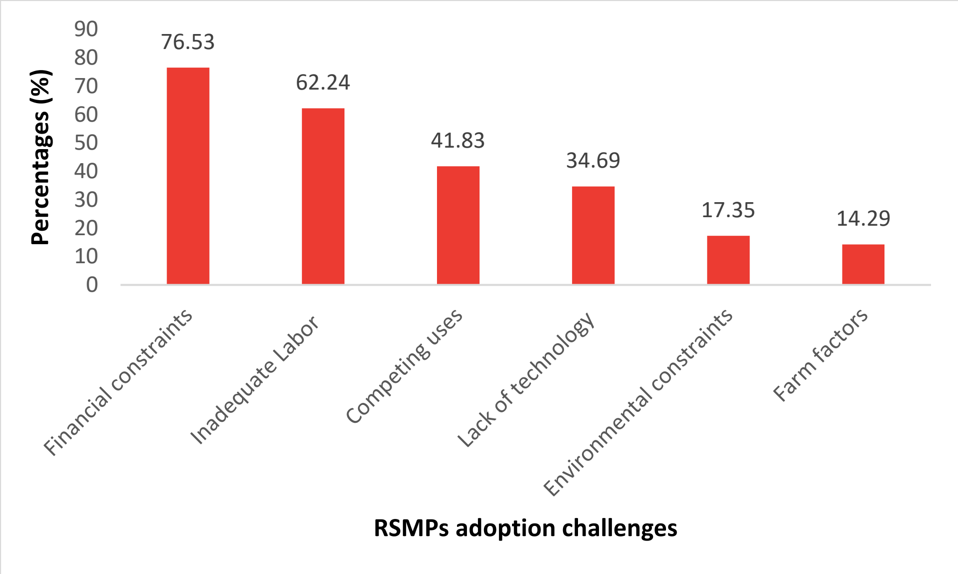


Figure 10. Challenges facing the adoption of RSMPs in the study area

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.

3.4 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 8.*

Table 8: 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 content 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.

3.5 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 11)*.

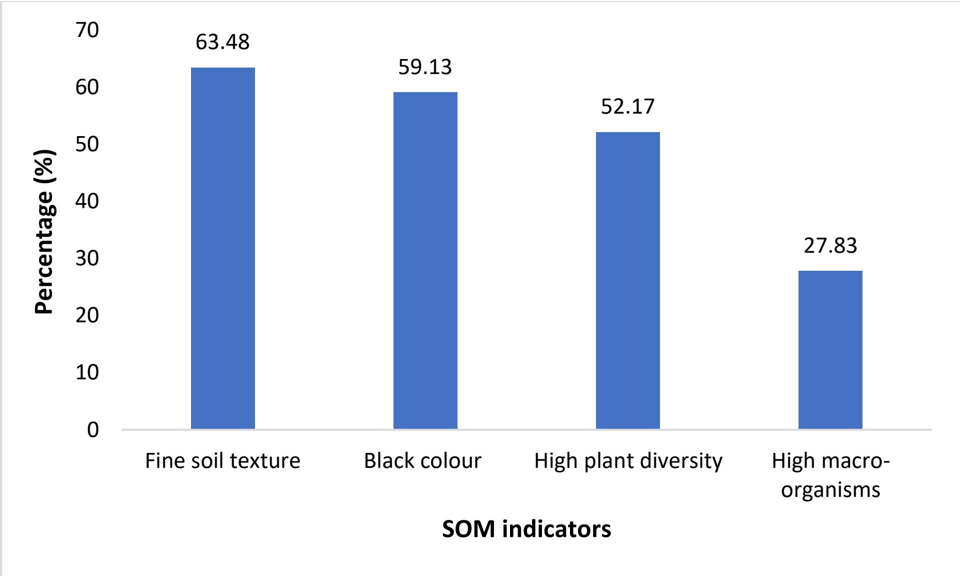


Figure 11: Indicators of soils with high SOM content (farmers' perception)

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 12*). 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).

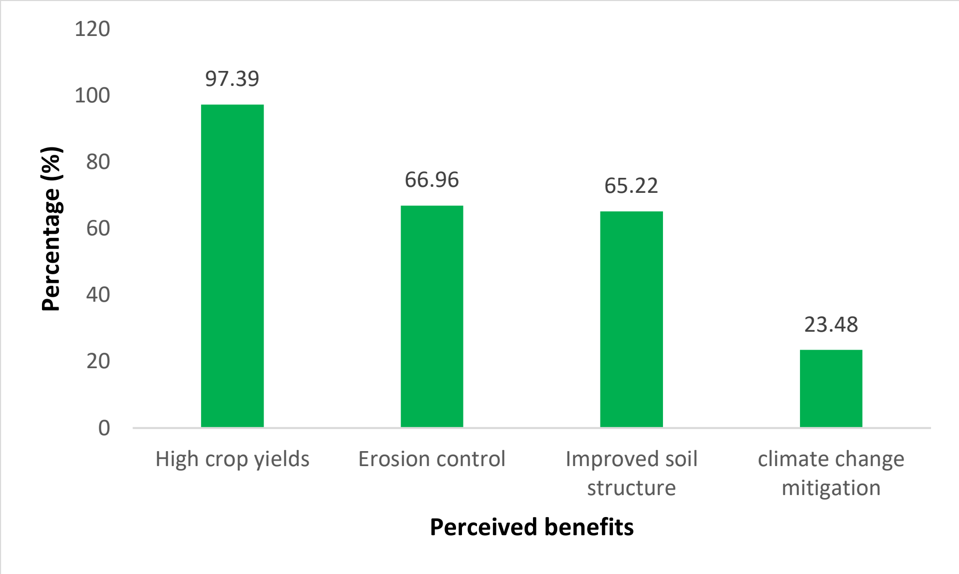


Figure 12: Farmers' perceived benefits of SOM on the eastern slopes of Mount Kenya

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 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.

4.2 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.

5. 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 a 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.

LIST OF PUBLICATIONS

1. **Rotich, B.,** Maket, I., Kipkulei, H. K. Ocansey, C.M., Justine, P.N., MohammedZein, M.A., Csorba, Á., & Michéli, E. (2024). Determinants of soil and water conservation practices adoption by smallholder farmers in the Central Highlands of Kenya. *Farming System*. https://doi.org/10.1016/j.farsys.2024.100081.

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3. Mohammedzein, M. A., Csorba, A., **Rotich, B.,** Justin, P. N., Mohamed, H. T., & Micheli, E. (2023). Prediction of some selected soil properties using the Hungarian Mid-infrared spectral library. *Eurasian Journal of Soil Science*, 12(4), 300-309. https://doi.org/10.18393/ejss.1309753 (Q3).

4. MohammedZein, M. A., Micheli, E., **Rotich, B.,** Justine, P. N., Ahmed, A. E. E., Tharwat, H., & Csorba, Á. (2023). Rapid Detection of Soil Texture Attribute based on Mid-Infrared Spectral Library in Salt Affected Soils of Hungary. *Hungarian Agricultural Engineering*, 42, 5–13. https://.www.doi.org/10.17676/HAE.2023.42.5.

5. Kipkulei, H. K. Bellingrath-Kimura, S. D., Lana, M., Ghazaryan, G., Baatz, R., Boitt, M., Chisanga, C. B., Rotich, B., & Sieber, S. (2022). Assessment of Maize Yield Response to Agricultural Management Strategies Using the DSSAT–CERES-Maize Model in Trans Nzoia County in Kenya. *International Journal of Plant Production*. https://doi.org/10.1007/s42106-022-00220-5 (Q2).

6. Alayan, R., **Rotich, B.,** & Lakner, Z. (2022). A comprehensive framework for forest restoration after forest fires in theory and practice: a systematic review. *Forests,* 13(9), 1354. https://doi.org/10.3390/f13091354 (Q1).

7. **Rotich, B.,** Csorba, A., & Micheli, E. (2022). Soil and Water Conservation in Kenya; practices, challenges, and prospects. *5th International Scientific Conference on Water*: Szarvas, Hungary.

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