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Impacts of climate-smart soil and water conservation practices and slope gradient on selected soil chemical properties in Eastern Ethiopia: A case study of the Kulkullessa Sub-watershed, Goro Gutu District

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Abstract

The productivity and sustainability of agricultural systems are heavily influenced by soil fertility and physicochemical properties. This study investigated the effects of climate-smart soil and water conservation (SWC) practices and slope gradient on selected soil physicochemical properties and soil organic carbon stock (SOCS) in the Kulkullessa Sub-Watershed of Goro Gutu District, Eastern Ethiopia. The research focused on farmland conserved by stone bunds (SB), bench terraces (BT), and grass strips (GS) five years post-implementation, across two slope gradients (15-20% and 21-30%). Twenty-four composite soil samples were collected from a depth of 0-20 cm and analyzed at the Haramaya University soil laboratory. Results demonstrated that climate-smart SWC practices significantly improved soil physicochemical properties and SOCS in the study area. Slope gradients also induced considerable variations in these parameters. Conserved farmland and areas with lower slope gradients exhibited higher clay content and lower sand fractions. Bench terraces were associated with lower bulk density (BD) and significantly higher total porosity ($p \leq 0.05$). Conserved farmlands showed higher electrical conductivity (EC) and lower pH values, both statistically significant ($p \leq 0.05$). Stone bunds were most effective in increasing soil organic matter (SOM) content and total nitrogen (TN). Climate-smart SWC practices also enhanced exchangeable bases in the farmlands. Cation exchange capacity (CEC) was significantly improved ($p \leq 0.05$) on farmland conserved by SB and BT. In conclusion, climate-smart SWC practices demonstrated substantial potential for improving agriculturally and environmentally relevant soil physicochemical properties and organic carbon stocks. These findings underscore the importance of such conservation measures in enhancing soil quality and promoting sustainable agriculture in the region.

Keywords: adaptation; climate-smart agriculture; micronutrients; mitigation; soil properties

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Introduction

Soil degradation is a major global problem, the effects of which may be felt most strongly in developing countries where large proportions of the population draw their livelihoods directly from the soil (Katherine *et al.*, 2015). Soil degradation in Sub-Saharan Africa (SSA) is a serious problem, which causes declines in agricultural productivity that has been linked to hunger and poverty. Ethiopia is one of the most well-endowed countries in sub-Saharan Africa in terms of natural resources. However, natural resource degradation in Ethiopia has been going on for centuries. Smallholder farmers in Ethiopia generally face widespread problems related to inappropriate cultivation, overgrazing, deforestation, soil erosion and soil fertility decline, water scarcity, lack of pasture and livestock feed, and fuel wood crisis. These problems are being exacerbated by increasing weather variability and climate change, which require urgent action and different approaches in the drylands and highland areas. Increasing weather variability and climate change are contributing to land and natural resource degradation by exposing soils to extreme conditions and straining the capacity of existing land management practices to maintain resource quality. Consequences include degradation of vegetation cover and loss of biodiversity, soil erosion, depletion of organic matter, reduced rainwater infiltration and water holding capacity of the soil, loss of productivity, and effects on wider ecological functions (Malo *et al,* 2012; Nortcliff *et al.*, 2011).

Several studies have been conducted in Ethiopia to ascertain the effects of soil conservation practices on soil physical and chemical properties. Studies conducted by Simret (2014), Lemma *et al.* (2015), Shimbahri *et al.* (2016), and Melkamu *et al.* (2019) focused on farmlands, enclosure of degraded forest, hilly sides, and pastoral lands with fewer parameters that indicate the necessity of further investigation. These studies have reported the significant effect of climate-smart SWC practices like soil and stone bunds, trenches, check dams, microbasins, and grass strips on soil physicochemical properties. Understanding the status and condition of soils and their properties is fundamental for making decisions about sustainable soil management practices that contribute to climate-smart land use. It needs to be backed up by laboratory testing for specific soil properties that can be identified through visual soil assessment with land users and technical experts to assess physical properties (texture, structure, water holding capacity, dispersion) and chemical properties (pH, nutrients, and salinity).

This study was carried out in Kulkullessa subwatershed from 351 ha of farmland that is situated on a 15-30% slope gradient and is not yet covered by climate-smart SWC Practices (GGDAO, 2019). In addition, most of the previous studies did not consider the effect of climate-smart SWC practices on plant micronutrients, which are essential from an agricultural productivity perspective. Therefore, this study was initiated with the general objective of investigating the effects of climate-smart SWC practices and slope gradients on selected soil physicochemical properties and soil organic carbon stock of the soil in the Kulkullessa Sub watershed, Goro Gutu District, Eastern Ethiopia.

Materials and Methods

Description of the study area

The study was conducted at Kulkullessa sub-watershed in Goro Gutu district, east Hararghe zone, Oromia Regional State, Ethiopia. The district is located 420 km east of Addis Ababa, along the main road to Harar, and 106 km northwest of the zonal capital, Harar City. Its administrative boundary is Somali Regional State to the north, Deder District to the south, Metta District to the east, and Doba District to the west (GGDAO, 2019). As revealed from GIS software, the Kulkullessa subwatershed exists between (9°23'15" and 9°26'15"N latitude and 41°20'40" and 41°21'55"E longitude) (Figure 1).

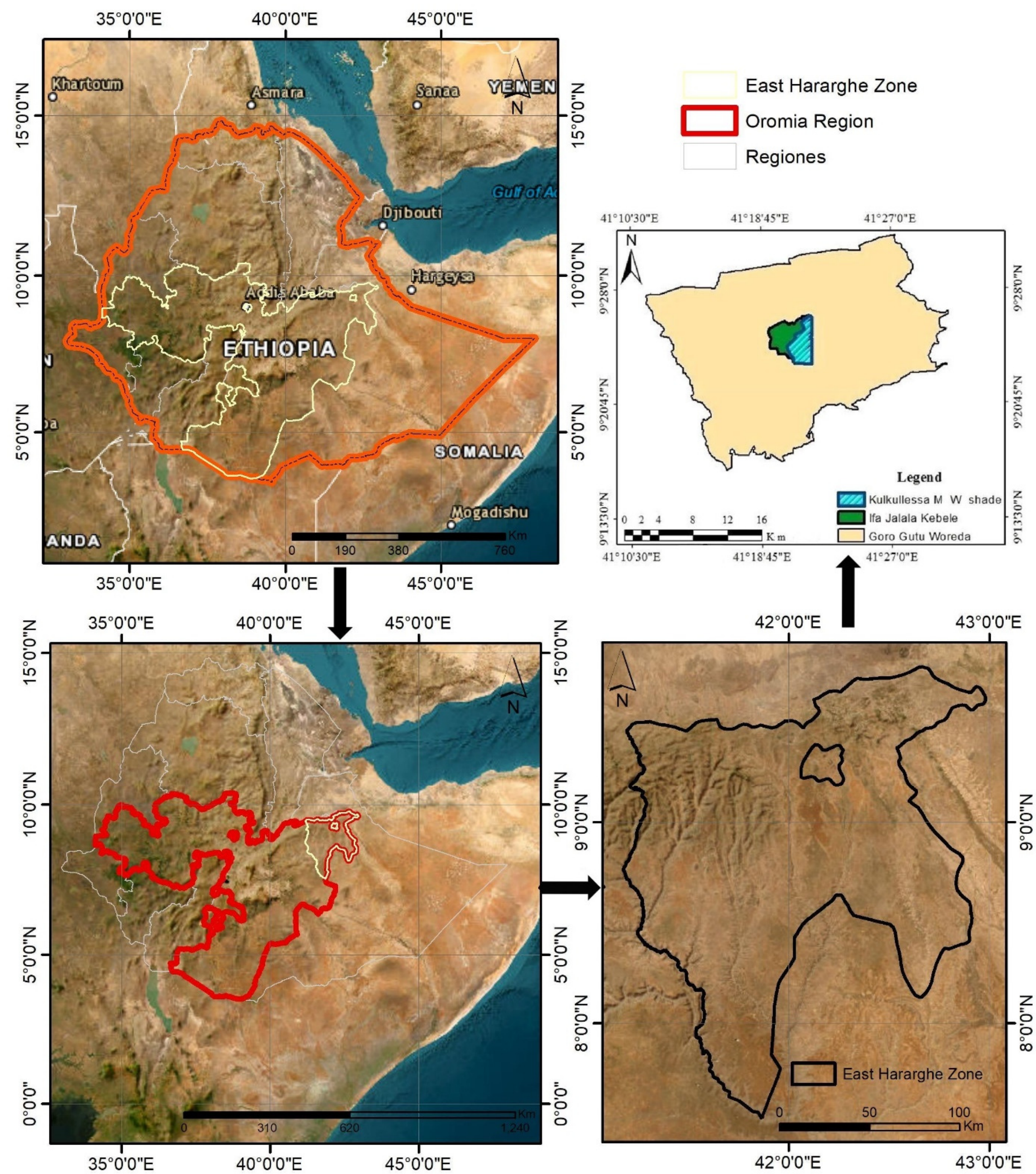

Figure 1. Map of the study area

Climate and topography

Topographically, the study area has ragged terrain within an elevation range of 1500 to 2200 meters above sea level. Kulkullessa subwatershed is agro-ecologically categorized in the midland (*Badda area*). The study area experiences a bimodal rainfall pattern. The main rainy season (locally called *Ganna*) is from June to the end of September, while the short rainy season (locally called *Badheessa*) extends from March to May (GGDAO, 2019). It receives an average annual rainfall (of 996.86 mm) whereas the average temperature is (21.45OC), respectively, KNMI (2021).

Soil sampling and preparation

Soil samples were collected from cultivated farmlands to assess the effect of climate-smart SWC practices and slope gradient on selected soil physiochemical properties and soil organic carbon stock in the Kulkullessa subwatershed, Ifa Jalala *kebele*. To reduce the heterogeneity in geologic and topographic conditions, closely located farmlands from intervening and no intervention was considered. Land that received similar land management practices at each slope category was carefully selected. In other words, the selected cultivated lands had a similar history in the application of chemical fertilizer and land management practices, and have been cultivated for similar crops, usually maize and sorghum, at least for the past five consecutive cropping seasons. The age of all climate-smart SWC practices selected for this study was five years from the date of construction (GGDAO, 2019).

The composite topsoil (0-20 cm) was taken from a plot of 2 × 2 m by considering the maximum width of structures. Soil sampling plot along diagonals from each corner and center of representative sampling plots with climate-smart SWC structures (Stone bunds, grass strips, and bench terraces) and without climate-smart SWC practice using a core sampler for bulk density and an auger sampler for the rest of the parameters at three replications was taken. Selected sampling spots were cleaned from the debris of plant residues and stones, and then the samples were collected properly. The subsamples were mixed thoroughly to produce about 1 kg of composite soil sample. In total, 24 composite soil samples were collected because the treatments were four SWC practices including non-conserved (control plot) at two slopes (15-20% and 21-30%). Soil samples were properly packed, labeled, and transported to Haramaya University Soil Laboratory. The geographic coordinates, slope, and altitude of each sampling plot site were recorded using GPS, clinometer, and altimeter, respectively. Then soil samples were air dried, ground, and passed through a 2 mm sieve for laboratory analysis of selected soil physicochemical properties except soil organic carbon and total nitrogen, in which case the soil was sieved with 0.5 mm mesh.

Laboratory analysis of selected soil properties

Physical properties

Determination of particle size distribution was carried out by the Bouyoucos hydrometer method and the soils were assigned to their textural class names based on the United States Department of Agriculture (USDA) soil textural triangle (USDA/SCS, 1987). The bulk density was determined from the undisturbed soil samples following the core method. The particle density (ρs) of soil is the oven-dried mass of soil (Ms) per unit volume of soil solids (Vs). Total soil porosity (*f*) was estimated from the values of bulk density *(ρb)* and particle density *(ρs)* as follows:

$$f(\%) = (1 - \frac{\rho b}{\rho s}) \times 100$$

where: f (%) = porosity, ρb = bulk density, ρs = particle density.

Soil water retention capacity at field capacity (FC, at - 0.33 bar) and permanent wilting point (PWP, at -15 bar) was measured by the pressure plate extraction method. Finally, the plant available water holding capacity (AWC) was calculated as the difference between soil water content at FC and PWP.

Chemical properties

Soil pH was determined using a pH meter with a combined glass electrode in a solution of 1:2.5 soil-to-water ratio. Electrical conductivity (EC) was measured by a conductivity meter on saturated soil paste extracts obtained by applying suction. To determine organic carbon (OC), the Walkley and Black (1934) method was employed in which the carbon was oxidized with a mixture of potassium dichromate in sulfuric acid solution. Soil organic carbon stock (SOCS) was estimated using the following equation as per Shimbahri *et al.* (2016) measured soil depth (i.e. 20 cm), BD (g cm^{-3}), organic carbon (%), and the sample soil excluding the coarse fragment, as follows:

$$\text{SOCS } (t\ ha^{-1}) = d * BD \times SOC*(1\text{- proportion of coarse fragment})$$

where: SOCS = Soil organic carbon stock, d = soil depth, BD = bulk density, SOC = soil organic carbon (%).

$$\text{Proportion of coarse fraction} = \frac{Total\ weight - Weight\ of\ fraction\ < 2\ mm}{Total\ weight} \times 100$$

The total nitrogen (TN) content in soils was determined using the Kjeldahl procedure (Sahlemedhin and Taye, 2000). Determination of available phosphorous (AP) was carried out by the Olsen (1954) method using sodium bicarbonate (0.5M $NaHCO_3$ at pH 8.5) as the extractant. Exchangeable bases (Ca^{2+}, Mg^{2+}, $K^{+,}$ and Na^+) were estimated by the ammonium acetate (1M NH4OAc at pH 7) extraction method. The exchangeable Ca^{2+} and Mg^{2+} in the extracts were determined by atomic absorption spectrophotometer (AAS), while a flame photometer was used to determine the contents of exchangeable K^+ and Na^+. Soil cation exchange capacity (CEC) was also determined by saturating the exchange sites with an index cation ($NH4^+$). The saturated soil was rinsed with ethanol to remove excess $NH4^+$. The soil was then rinsed with (1N NaCl) to leach $NH4^+$ from the exchange site. This leachate was then analyzed by steam distillation and titration which determined the $NH4^+$ adsorbed on the soil exchange complex (Burt, 2009). The base saturation (BS) was computed as the percentage of the sum of the exchangeable bases to the CEC of the soil.

Data Analysis

To analyze the effect of climate-smart SWC practices and slope gradient on selected soil properties and soil organic carbon stock, the GLM procedure with two-way ANOVA was used and mean comparisons were made using the Tukey HSD test at $p \leq 0.05$. Pearson correlation was also used to correlate different soil parameters across climate-smart SWC practices. The analysis was conducted by statistical software (SPSS) version 20.

Results and Discussion

Effect of climate smart SWC practices and slope gradient on selected soil chemical properties

Soil pH and electrical conductivity

The results indicated the effect of climate-smart SWC practices on soil reaction (pH) and electrical conductivity. The mean value of pH in farmland situated on a lower slope gradient (15-20%) and conserved by SB was found lower than the other SWC practices and non-conserved farmlands. Likewise, the value of pH obtained on farmland conserved by stone bund was the lowest value, followed by the value recorded on farmland protected by the grass strip. Therefore, the mean difference of pH on farmland located on the lower slope and conserved by SB and GS was exhibited significant variation ($p \leq 0.05$) in contrast to non-conserved farm lands situated on a similar slope gradient. The higher value of pH was recorded on the higher slope gradient

(21-30%) and conserved by the bench terrace (Table 1). The lowest pH value found on farmland conserved by stone bunds and grass strips might be due to the higher organic matter content and the nature of parent materials.

The rating of pH from 6.2-6.7 is slightly acidic, 6.7-7.3 is neutral, whereas 7.3-7.9 is slightly alkaline (Flynn, 2015). The mean of pH value in the study area was slightly acidic on farmland conserved by stone bunds and grass strips. However, the pH value recorded on farmland conserved by bench terrace and situated on a lower slope gradient (15-20%) was found neutral, whereas the higher value of pH value recorded on farmland situated on a higher slope gradient (21-30%) and conserved by BT was found slightly alkaline. Generally, the recorded pH values in the study area were slightly acidic, neutral to slightly alkaline, and mostly favorable for most of the crops. A similar study by Simret (2014) and Melkamu *et al.* (2019) found a lower pH value on farmlands conserved by climate-smart SWC practices than on non-conserved farmlands.

The pH value of the study area was found statistically significant variation at ($p \leq 0.05$) due to slope difference. Accordingly, the higher positive value for pH was recorded on farmland conserved by the bench terrace on (20-30%) in contrast to the value recorded on the (15-20%) slope gradient. The difference perhaps resulted from more accumulation of organic matter on the lower slopes due to the decreased erosive power of erosion agents and accumulation of sediments from the higher slope that could inevitably increase the deposition of nutrient-rich soil particles including organic matter.

The value of electrical conductivity did not bring significant variation between conserved and non-conserved farmlands in the study area. However, the higher mean value of EC was recorded on conserved farmlands. Accordingly, the highest EC (0.455 and 0.33) mmhos/cm was recorded on lower and higher slope gradients on farmland conserved by stone bund. The electrical conductivity value of the study area ranges from (0.13 mmhos/cm) recorded on non-conserved farmland located on a higher slope gradient and (0.455 mmhos/cm) recorded on farmlands conserved by stone bund on a lower slope gradient which is considered very low and best for sensitive plants (Table 1). The reason for the higher value of EC on farmland conserved byclimate-smart SWC practices might be due to the higher quantity of SOM content and exchangeable bases that resulted in a more concentrated soil solution that could have more ions in the soil and increase electrical conductivity. The statistically significant value of EC was not observed on farmland due to slope difference. However, at the lower slope gradient (15-20%), a comparatively greater mean value for EC was recorded (Table 1). In line with this study, other studies indicated the decreasing trends of EC with increasing slope from gentle to steep (Mathewos *et al.,* 2016).

Soil organic matter content and total nitrogen

The highest value of SOM content was recorded on farmland conserved by SB situated on both slope gradients (15-20% and 21-30%) in contrast to farmland conserved by BT, GS, and NCF in the study area. Likewise, the farmland conserved by SB, BT, and GS resulted in higher mean values of SOM content than the value recorded on non-conserved farmlands. Accordingly, the mean value of SOM content recorded on farmland conserved by SB was more than the value of SOM content recorded on NCF by 0.99% and 0.75% on lower and higher slope gradients respectively. Whereas 0.62% and 0.56% more SOM content on farmland conserved by BT on both slope gradients and 0.45% more SOM content was recorded on farmland conserved by grass strip situated on the lower slope gradient in comparison to the value of SOM content recorded on non-conserved farmlands of the study area.

The reason for the lower values of SOM content recorded on farmland conserved by BT in contrast to farmland conserved by SB might be occurred from the significant disturbance and mixing oftop soil with sub-soil on farmland conserved by BT at the time of construction. The other reason might be due to the exceptionally restricted free grazing on farmland conserved by the bench terraces during the dry season which could reduce the addition of organic matter from livestock dung. Further, the lower value of SOM content in farmland conserved by grass strips might have resulted from its lower potential in protecting soil erosion than farmland conserved by other climate-smart SWC practices. The mean of SOM content in the study area ranges from 1.255% on NCF situated on (21-30%) slope gradient and 2.43% on farmland conserved by stone bund and situated on (15-20%) slope gradient (Table 1). However, the mean variation of SOM content between conservation practices on farmland as well as between conserved farmland and NCF was not found statistically significant. The main reasons might be related to the age of conservation practices which was only five years from the date of construction.

Table 1. Effect of climate-smart SWCP and slope gradient on selected soil chemical properties*

No	SWC Practices	Soil parameters	Mean on SWCP	Mean on NCF	Mean difference	p-value
			Slope (15-20%)			
1	SB (Stone bund)	pH	6.28	7.3	-1.023*	0.001
		EC (mmhos/cm)	0.455	0.157	0.299	0.132
		SOM %	2.43	1.45	0.986	0.386
		TN %	0.097	0.049	0.048	0.723
		AP (mg/kg)	29.48	28.35	1.13730	0.999
2	BT (Bench terrace)	pH	7.25	7.3	-0.0467	1
		EC (mmhos/cm)	0.433	0.1567	0.2763	0.190
		SOM %	2.06	1.45	0.616	0.848
		TN %	0.085	0.049	0.035	0.920
		AP (mg/kg)	28.44	28.35	0.097	1
3	GS (Gras strip)	pH	6.63	7.3	-0.6733*	0.039
		EC (mmhos/cm)	0.26	0.1567	0.11	0.960
		SOM %	1.89	1.45	0.448	0.966
		TN %	0.092	0.049	0.0422	0.825
		AP (mg/kg)	25.97	28.35	-2.37	0.956
No	SWC Practices	Soil parameters	Mean on SWCP	Mean on NCF	Mean difference	p-value
			Slope (21-30%)			
1	SB (Stone bund)	pH	6.7	7.22	-0.5233	0.165
		EC (mmhos/cm)	0.33	0.13	0.199	0.539
		SOM %	2	1.255	0.7508	0.690
		TN %	0.088	0.049	0.039	0.874
		AP (mg/kg)	30	24.98	5.037	0.375
2	BT (Bench terrace)	pH	8.05	7.22	0.823*	0.008
		EC (mmhos/cm)	0.3	0.13	0.168	0.721
		SOM %	1.8	1.255	0.56	0.899
		TN %	0.06	0.049	0.014	1
		AP (mg/kg)	27.55	24.98	2.57	0.935
3	GS (Gras strip)	pH	6.5	7.22	-0.753*	0.017
		EC (mmhos/cm)	0.22	0.133	0.09	0.984
		SOM %	1.1	1.255	-0.19	1
		TN %	0.05	0.049	0	1
		AP (mg/kg)	26.25	24.98	1.27	0.999

* pH = Potential of hydrogen, NCF = Non-Conserved Farmland, SWCP= Soil and Water Conservation Practices, EC = Electrical conductivity, SOM = Soil organic matter, TN = Total nitrogen, AP =Available phosphorous, (*) = The mean difference is significant at 0.05 level, Mean difference = The difference of mean value between Climate smart SWCP and NCF.

The results of TN mostly exhibited similar trends with soil organic matter content. The variation in the results of TN recorded on conserved and non-conserved farmland was statistically insignificant. However, the recorded mean value of TN on conserved farmland was more than the value recorded on non-conserved farmlands on both slope gradients (Table 1). Among the conserved farmlands, a greater value (0.097%) of TN was recorded on farmland conserved by stone bund, whereas 0.092% on farmland protected by grass strips and 0.085% was found on farmland conserved by the bench terrace. All results recorded were more than the value recorded on non-conserved farmlands, which was only 0.049% of the total nitrogen content in the study area. In contrast to non-conserved farmlands, farmland conserved by stone bund resulted in 49.48% of TN, whereas the value on grass strips and bench terraces exceeded the TN value of non-conserved farmlands by 46.73% and 42.35% respectively (Table 1). This might be a result of the effectiveness of conservation practices even though the age of the structures was only five years since conservation practices were constructed on farmland. The result was in line with Shimbahri *et al.* (2016) and Dejene (2017) who reported higher soil organic matter and total nitrogen content on conserved farmlands than on non-conserved farmlands.

Despite the higher mean value observed on farmlands situated on a lower slope gradient (15-20%) than on farmlands positioned on a steeper slope gradient (21-30%), the effect of slope gradient on SOM content and TN was found statistically insignificant. The mean value of SOM content in farmlands positioned on a lower slope gradient and conserved by SB was 0.426% more than the value recorded on a higher slope gradient. Further, values of SOM content on farmlands conserved by GS and BT as well as on non-conserved farmland located on lower slope gradient (15-20%) exceeded the values recorded on farmlands situated on higher slope gradient (21-30%) by 0.829%, 0.2465%, and 0.19% respectively (Table 1). In the case of TN content, farmland situated on a lower slope gradient and conserved by SB, GS, and BT resulted in 9.28%, 46.74%, and 28.57% of TN percentage than farmland conserved by the same SWC practices but positioned on a steeper slope gradient (21-30%) respectively (Table 1). In line with this study, other findings reported significant variation based on the differences in slope gradients that higher values of SOM content and TN were found in farmland situated on gentle slopes than steeper slopes. These results were shown as there was an increase in the percent of soil organic matter and total nitrogen content with a decreasing slope gradient. However, the values recorded on farmlands positioned on strongly sloping (10-15%) and moderately steep slopes (15-30%) were not significant from each other Mulugeta (2015); Mathews *et al.* (2016) and Mohammed (2019).

According to Murphy *et al.* (2012), the interpreted result for the Kulkullessa subwatershed found that the rating of SOM content in farmland conserved by grass strip on slope gradient (15-20%) was found medium while the value of slope gradient (21-30%) was found low. Similarly, the value of SOM content recorded on non-conserved farmlands situated on slope gradients was found low. Furthermore, the value of SOM content recorded on farmland conserved by stone bund was found high on both slope gradients, whereas for farmland conserved by bench terrace situated on both slope gradients, the level of SOM content resulted in a medium range.

According to Hazelton and Murphy (2016) interpretation results, the total nitrogen percentage description is very low if < 0.05%, low 0.05-0.15%, medium 0.15-0.25%, high 0.25-0.50%, and very high if > 0.5%. Based on this rating, the total nitrogen content of the Kulkullessa sub-watershed was labeled as low content of farmland conserved by climate, smart SWC practices, and non-conserved farmlands of the study area.

Available phosphorous

The effect of climate-smart SWC practices on the value of AP recorded on farmland was found statistically insignificant. Despite the values that were not found, significant, farmlands conserved by climate-smart SWC practices resulted in higher AP than the values recorded on non-conserved farmlands. The higher value of available phosphorous was recorded on farmlands conserved by stone bunds and bench terraces on both slope gradients (15-20 and 21-30%), followed by farmland conserved by GS on higher slope gradients respectively (Table 1). Comparatively insignificant values for this observation might be due to the close value of SOM content in conserved farmland and non-conserved farmland available phosphorous is related to soil organic matter content.

The influence of slope gradient was also found statistically insignificant on the value of available phosphorous. Relatively, there was a higher mean value of available phosphorous on farmlands situated on a lower slope gradient than farmlands located on a steeper slope gradient (Table 1). Likewise, studies indicated not only higher but also statistically significant values of AP on conserved farmlands situated on the lower slope gradient Mulugeta (2015), Mathewos *et al.* (2016); Nnabude *et al.* (2016); Chota (2019) and Melkamu *et al.* (2019). This might result from the potential of conservation practices that reduce the removal of some applied phosphorous fertilizer from farmlands. According to Olsen's (1982) phosphorous soil test interpretation results, the amount of AP range between 20 ppm and 40 ppm is sufficient for plant growth and development. Accordingly, the amount of available phosphorous recorded on the farmlands of the study area ranges between 24.98-30 mg/kg, which exists within the range that is sufficient for plant growth and development. Hence, it is not currently a limiting factor for crop production. Thus, management interventions to reduce the depletion of AP and keep the current status beyond the critical level are essential in the study area.

Exchangeable bases

The amount of exchangeable calcium (Ca^{2+}) on farmlands due to the difference in climate-smart SWC practices was statistically insignificant. The mean value of exchangeable (Ca^{2+}) on farmland conserved by stone bund was more than the value recorded on non-conserved farmlands by (2.66 and 2.41(cmol (+)/kg of soil respectively on farmland situated on (15-20% and 21-30%) slope gradients. Similarly, the value of exchangeable Ca^{2+} recorded on farmlands conserved by BT and Grass strips were 2.19 and 2.05 (cmol (+)/kg of soil for farmland situated on a lower slope gradient and 2.48 and 1.7 (cmol (+)/kg of soil for farmland situated on higher slope gradient respectively (Table 2). The higher mean value for (Ca^{2+}) was recorded on farmland conserved by a stone bund followed by a bench terrace and grass strip. The effect of slope difference on (Ca^{2+}) was found insignificant. However, farmlands situated on a lower slope gradient resulted in higher (Ca^{2+}) contents (Table 2). Therefore, the obtained differences in values of (Ca^{2+}) recorded on farmlands resulted from the difference in both climate's smart SWC practices and the difference in slope gradient. According to rating standard of extract Ca^{2+} (cmol (+)/ kg) of soil Hazelton and Murphy (2016), the amount of calcium recorded on the farmlands of Kulkullessa subwatershed was above 2 (cmol (+)/ kg) and below 5 (cmol (+)/ kg) which was considered as low level except the medium level of Ca^{2+} was recorded on farmland conserved by stone bund situated onlower slope gradient.

Exchangeable magnesium was shown a similar situation with exchangeable calcium, hence it did not bring significant variation due to the difference in conservation status on farmland. Thus, the mean value of exchangeable magnesium on non-conserved farmland was lower than the mean value of exchangeable magnesium recorded on farmland conserved by BT and situated on a lower slope (15-20%) and higher slope gradient (21-30%) by 54.7 and 53.4% respectively. Likewise, more value of exchangeable magnesium percentage (47.86% and 46%) was recorded on farmland conserved by SB and 49.17 and 34.16% on farmland conserved by grass strip in contrast to non-conserved farmland situated on both slope gradients respectively (Table 2).

Besides a higher mean value was recorded on farmland situated on a lower slope gradient (15-20%) than on a steeper slope gradient (21-30%), the effect of slope on exchangeable magnesium was found insignificant. However, farmland situated on a lower slope gradient was found more effective in the accumulation of exchangeable magnesium (Table 2). Similarly, Mulugeta (2015), Mathewos *et al.* (2016), Dejene (2017), Chota (2019) and Melkamu *et al.* (2019) reported exchangeable calcium (Ca^{2+}) and (Mg^{2+}) was significantly ($p \leq 0.01$) affected by the land use types other than slope differences. There were increasing trends of exchangeable basic cation concentration in farmland situated on moderately steep to gently sloping gradients, which might be due to the loss through runoff and erosion in the high-sloping areas and accumulation in areas having lower slope gradients (Mulugeta, 2015). A rating by Hazelton and Murphy (2016) the recorded amount of Mg^{2+} was found medium on non-conserved farmlands and high on all farmlands conserved by SB, BT, and grass strips.

Table 2. Effect of climate-smart SWCP and slope gradient on soil CEC and exchangeable bases*

No	SWC practices	Soil parameters	Mean on SWCP	Mean on NCF	Mean difference	p-value
			Slope (15-20%)			
1	SB (Stone bund)	Ca^{2+} (cmol (+)/ kg	5.05	2.39	2.66	0.243
		Mg^{2+} (cmol (+)/ kg	3.51	1.83	1.68	0.339
		K^{+} (cmol (+)/ kg	0.699	0.147	0.55	0.597
		Na^{+} (cmol (+)/ kg	0.097	0.063	0.034	0.933
		CEC (cmol (+)/ kg	51.26	27.75	23.5*	0
2	BT (Bench terrace)	Ca^{2+} (cmol (+)/ kg	4.58	2.39	2.19	0.453
		Mg^{2+} (cmol (+)/ kg	4.034	1.83	2.21	0.107
		K^{+} (cmol (+)/ kg	0.484	0.147	0.337	0.939
		Na^{+} (cmol (+)/ kg	0.085	0.063	0.021	0.995
		CEC (cmol (+)/ kg	38.33	27.75	12*	0.02
3	GS (Gras strip)	Ca^{2+} (cmol (+)/ kg	4.44	2.39	2.05	0.53
		Mg^{2+} (cmol (+)/ kg	3.6	1.83	1.78	0.283
		K^{+} (cmol (+)/ kg	0.569	0.147	0.42	0.837
		Na+ (cmol (+)/ kg	0.092	0.063	0.028	0.974
		CEC (cmol (+)/ kg	26.33	27.75	-1.418	1
No	SWC practices	Soil parameters	Mean on SWCP	Mean on NCF	Mean difference	p-value
			Slope (21-30%)			
1	SB (Stone bund)	Ca^{2+} (cmol (+)/ kg	4.35	1.939	2.41	0.343
		Mg^{2+} (cmol (+)/ kg	3.17	1.712	1.45	0.507
		K^{+} (cmol (+)/ kg	0.8	0.105	0.69	0.332
		Na^{+} (cmol (+)/ kg	0.09	0.049	0.039	0.874
		CEC (cmol (+)/ kg	41.67	19.8	21.87*	0.000
2	BT (Bench terrace)	Ca^{2+} (cmol (+)/ kg	4.41	1.94	2.48	0.316
		Mg^{2+} (cmol (+)/ kg	3.67	1.71	1.95	0.195
		K^{+} (cmol (+)/ kg	0.42	0.1	0.316	0.956
		Na^{+} (cmol (+)/ kg	0.049	0.049	0	1
		CEC (cmol (+)/ kg	28.33	19.8	8.53	0.162
3	GS (Gras strip)	Ca^{2+} (cmol (+)/ kg	3.64	1.94	1.7	0.724
		Mg^{2+} (cmol (+)/ kg	2.6	1.7	0.92	0.897
		K^{+} (cmol (+)/ kg	0.569	0.1	0.46	0.767
		Na^{+} (cmol (+)/ kg	0.049	0.049	0	1
		CEC (cmol (+)/ kg	26	19.8	6.199	0.490

* NCF = Non-Conserved Farmland, SWCP= Soil and Water Conservation Practices, Ca^{2+} = Calcium, Mg^{2+} = Magnesium, K^{+} = potassium, Na^{+} = Sodium, CEC = Cation exchange capacity, (*) = The mean difference is significant at 0.05 level, Mean difference = The difference of mean value between Climate smart SWCP and NCF.

The recorded mean value for exchangeable (K^+) obtained on farmland conserved by stone bund was more than the value recorded on non-conserved farmland by (0.55 and 0.69) (cmol (+)/ kg, respectively on farmland that existed on higher and lower slope gradients. Further, more (K^+) values of 0.337 and 0.316 (cmol (+)/ kg were recorded on farmland conserved by the bench terrace. In contrast to non-conserved farmlands, more 0.42 and 0.46 (cmol (+)/ kg of exchangeable (K^+) was recorded on farmland conserved by grass strips situated on lower slope gradient (15-20%) and higher slope gradient (21-30%) respectively (Table 2).

In a similar way to Ca^{2+} and Mg^{2+}, the effect of slope on the value of exchangeable potassium recorded on farmland was found statistically insignificant. The recorded value of potassium was found higher on a lower slope gradient. Accordingly, more potassium value (0.042 and 0.063 (cmol (+)/ kg) was, respectively, recorded on farmland conserved by BT and GS which is situated on lower slope gradients in contrast to the value recorded on farmland that existed on higher slope gradients (Table 2). A similar study indicated an insignificant effect of slope on the value of potassium recorded on farmland situated on both strong slopes and moderately steep slopes (Mulugeta, 2015). This might be due to a narrower range of the considered slope difference in this study. According to the soil test interpretation results by Hazelton and Murphy (2016), the potassium content of the study area on farmland situated on both slope gradients (15-20 and 21-30%) was found high on farmland conserved by SB, medium on farmland conserved by BT and GS whereas very low on non-conserved farmlands that need a significant application for plant growth and development.

The effect of climate-smart SWC practices and slope gradient was insignificant on exchangeable sodium. In the study area, the recorded sodium percentage on conserved and non-conserved farmland was found very low. Sodium content below the level of 0.1 (cmol (+)/ kg is considered very low (Hazelton and Murphy, 2016). The observed result of sodium level on the farmland of this subwatershed was found very low. For this reason, it is at an acceptable level and not restrained for plant growth and development. The recorded value of low exchangeable sodium in this study area might be due to the study area having no irrigation water and completely practicing rain-fed agriculture. Additionally, rainfall in the study area might be enough to lich the accumulation of sodium from the top layer of the considered soil depth.

Cation exchange capacity

Cation exchange capacity was highly influenced by climate-smart SWC practices. The mean difference between farmland conserved by climate-smart SWC practices and non-conserved farmland situated on slope gradients (15-20) and (21-30%) were 23.5 and 21.87 (cmol (+)/ kg respectively on farmland conserved by stone bund whereas (12 and 8.53) (cmol (+)/ kg of soil) for farmland conserved by bench terrace respectively. The differences were found statistically significant ($p \leq 0.01$) on farmland conserved by stone bunds situated on both slope gradients and on lower slope gradients for farmland conserved by bench terraces in contrast to non-conserved farmlands of the study area (Table 2). However, the result of CEC on farmland conserved by grass strip was not found statistically significant when the mean value was compared with the recorded value of CEC on non-conserved farmland of the study area. The higher values recorded on farmlands conserved by climate-smart SWC practices were due to higher organic matter content (Table 1) and clay content (Table 1) in contrast to the values recorded onnon-conserved farmlands. Similarly, Abay *et al.* (2016) found a statistically significant variation of CEC recorded between conserved and non-conserved farmlands with a high positive value for conserved farmlands.

The slope was also the other factor that was considered to evaluate its consequence on the cation exchange capacity of soil in the study area. The higher value of 51.26 (cmol (+)/ kg soil) of CEC was recorded on farmland conserved by SB situated on a lower slope gradient (15-20%), whereas the lower value of CEC 19.8 (cmol (+)/ kg was recorded on non-conserved farmland situated on (21-30%) slope gradient (Table 2). This might have happened due to the higher SOM content and clay content recorded on farmland located on a lower slope gradient. Previous studies by Mulugeta (2015) and Chota (2019) reported an increasing tendency of CEC with decreasing slope gradient.

According to the soil test interpretation, the result recommended by Hazelton and Murphy (2016), the soil of the study area resulted in very high CEC on farmland conserved by SB and high on farmland conserved by BT and GS situated on both slope gradients. Furthermore, the mean value of CEC recorded on NCF was labeled as high on the lower slope gradient and medium on a higher slope gradient. This might be due to influencing factors such as pH value, which resulted in slightly acidic, neutral to slightly alkaline levels. Furthermore, SOM content in conserved farmlands resulted in medium to high levels that could contribute to higher cation exchange capacity. Additionally, the type of clay content might be the other contributing factor to the high CEC of the study area.

Conclusions

Based on the abstract provided, the study concludes that climate-smart soil and water conservation (SWC) practices have a significant positive impact on soil physicochemical properties and soil organic carbon stock (SOCS) in the Kulkullessa Sub-Watershed of Eastern Ethiopia. The implementation of stone bunds, bench terraces, and grass strips over five years resulted in marked improvements in soil quality across various slope gradients, effectively enhancing soil structure, increasing organic matter content, improving nutrient retention, and boosting overall soil fertility. These findings highlight the potential of climate-smart SWC practices as valuable tools for sustainable land management and agricultural productivity in the region. To capitalize on these results, several recommendations can be made. First, the widespread adoption of climate-smart SWC practices, particularly stone bunds and bench terraces, should be encouraged across similar agroecological zones in Ethiopia and beyond. Long-term monitoring programs should be established to assess the continued effects of these conservation practices on soil properties and crop yields over extended periods. An integrated approach to soil conservation, combining physical structures with biological measures, should be promoted for maximum effectiveness. Additionally, slope-specific SWC strategies should be developed and implemented, taking into account the observed variations in soil properties across different gradients. Capacity building through training and technical support for farmers on proper implementation and maintenance of these practices is crucial. Policy support, such as subsidies or other financial incentives, should be advocated to encourage adoption. Further research should be conducted to quantify economic benefits, investigate climate change mitigation potential, and explore effects on soil microbial diversity. Tailored, site-specific recommendations should be developed based on local conditions. Community engagement and knowledge dissemination platforms should be established to ensure widespread participation and continuous improvement of SWC strategies. By implementing these recommendations, stakeholders can leverage the study's findings to enhance soil conservation efforts, improve agricultural productivity, and promote sustainable land management in the region.

Author contributions

The authors made the following contributions to this paper: Conceptualization (AMA, FS); methodology (MAA, FS, AA); software (MAA); validation, (FS, AA); formal analysis (MAA, CP); investigation (MAA); resources (AMA); data curation (AMA); writing – original draft preparation (AMA); writing – review and editing (CP); supervision (FS, AA).

All authors have read and agreed to the published version of the manuscript.

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Conflict of interests

The authors declare no conflict of interest.

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