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Patterns of Nutrients Cycling and Soil Quality under Different Soil Conservation Practices: The Case of Amalake Watershed, Gidabo Sub-basin, South Ethiopia

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Abstract

Soil conservation practices have varying long-term effects on soil quality and nutrient cycling, making it essential to identify the most effective, ecology-specific methods. This study in the Amalake watershed, Gidabo sub-basin, investigated the long-term impacts of different conservation practices: soil bund (SB), micro-basin (MB), fanya-juu (FJ), and a control sample (CS) on soil quality indicators. Bulk soil samples were analyzed for physicochemical properties using standard methods. Principal component analysis (PCA) identified key indicators bulk density (BD), pH, water-stable aggregates (WSA), moisture content (MC), soil organic matter (SOM), and cation exchange capacity (CEC) — to calculate a soil quality index (SQI). All three soil conservation practices significantly ($p < 0.01$) improved properties such as BD, pH, WSA, MC, SOM, and CEC. The most effective practice, SB, resulted in changes of 28.57% (BD), 74.35% (WSA), 14.48% (MC), 21.05% (CEC), and 100% (SOM) compared to the control. SB also significantly increased the contents of Ca^{2+} (50.41%), Mg^{2+} (36.55%), and K^{+} (100%). However, the impacts on micronutrients were inconsistent. Additionally, SB yielded the highest SQI values across upper (0.68), middle (0.54), and lower (0.86) slopes. Overall improvements in soil indicators followed the order: SB > MB > FJ. Therefore, SB is the most effective soil conservation practice for enhancing nutrient cycling and soil quality in steep, variable landscapes like the Amalake watershed.

Keywords/Phrases: Nutrient cycling, Soil conservation, Soil quality, Soil quality indicators

1 Introduction

Soil quality (SQ) serves as a vital measure of environmental sustainability and the efficacy of soil management techniques (Osgoz *et al*., 2013; Vassilios *et al*., 2018). It indicates the capacity of soil to function as a substrate for plant development, thereby making the study of SQ essential for assessing the success of particular soil management strategies (Viana *et al*., 2014; Mulat *et al*., 2021). Soil quality is influenced by various land use systems, including overgrazing, deforestation, excessive trafficking, erosion, repeated cultivation, industrialization, and urbanization (Fazekašová *et al*., 2011; Agnieszka *et al*., 2019). Understanding SQ is vital for evaluating the suitability and sustainability of soil conservation planning and management policies (Van Leeuwen *et al*., 2015; Pezzuolo *et al*., 2017).

Assessing soil quality indicators (SQI) is complex due to the numerous interactions within the soil environment (Sánchez-Navarro *et al*., 2015; Selmy *et* *al*., 2021). Therefore, a comprehensive evaluation of soil quality requires examining both static and dynamic biogeochemical and physical properties to determine their influence on management outcomes. The environmental impacts of SQ reduction often become apparent only over an extended period, as soils have a capacity to buffer changes induced by external conditions. Additionally, the complex and dynamic nature of soils, along with the interactions between their properties, complicates the differentiation between variations resulting from natural and anthropogenic factors. After assessing SQ indicators, it is essential to identify ecology-specific soil conservation practices that improve both soil productivity and overall environmental health. Selecting specific SQI for evaluating SQ in a given ecological context can lead to the identification of effective and sustainable land use and soil conservation practices (Mulat *et al*., 2021; Selmy *et al*., 2021).

Overall, the objective of SQ assessment is to sustain and improve long-term agricultural productivity as well as environmental health (Vasu *et al*., 2016; Selmy *et al*., 2021). Consequently, it is essential to examine the comparative effects of various soil management techniques in particular regions to comprehend the dynamic alterations in soil physicochemical characteristics and to determine the most effective management strategies. In this study, three widely recognized soil management practices—soil bund (SB), micro-basin (MB), and fanya-juu (FJ)—have been implemented for over a decade (Negasa *et al*., 2017). This research aims to study the long-term impacts of these conservation activities on SQI and selected physicochemical characteristics.

While the importance of soil quality assessment is well-established, significant gaps remain in its localized application. Specifically, there is a lack of empirical, long-term comparative studies evaluating the effectiveness of specific soil conservation structures—namely, soil bunds, micro-basins, and fanya-juu—on a comprehensive set of soil quality indicators within the same agro-ecological setting. Previous research has often focused on erosion control or single parameters, but a holistic assessment integrating multiple physicochemical properties to determine the most effective practice for improving overall soil health in the study region is absent.

In the studied regions, SB, MB, and FJ structures have been implemented for over a decade to combat land degradation and improve productivity. However, it remains quantitatively unclear which of these practices most effectively enhances soil quality and physicochemical properties in the long term. Without a systematic evaluation of their relative impacts, farmers and policymakers lack the evidence-based knowledge needed to select, promote, and optimize the most sustainable and beneficial soil conservation practices for local conditions.

This study is significant as it provides critical, data-driven insights into the long-term efficacy of major soil conservation practices. The findings will directly inform local agricultural extension services and government agencies in formulating evidence-based land management policies. For farmers, the results will guide the adoption of the most effective practices to improve soil health, thereby enhancing crop productivity and sustainability. Furthermore, the research contributes to the broader scientific understanding of SQ assessment by developing a framework for evaluating conservation practices in similar agro-ecosystems.

The primary goal of this research is to evaluate and contrast the long-term effects of SB, MB, and FJ structures on soil quality. This goal will be accomplished through the following specific objectives:

1. To assess the impact of SB, MB, and FJ practices on essential soil physicochemical characteristics (including soil organic matter, texture, bulk density, pH, available phosphorus, total nitrogen, and cation exchange capacity).
2. To compute a Soil Quality Index (SQI) for each conservation method and evaluate them in comparison to a control (non-conserved) plot.
3. To determine the most effective soil conservation method for improving overall soil quality and health within the study area.

2 Materials and Methods

2.1 Description of the Study Area

This research was carried out in the Amalake watershed, situated within the Gidabo basin, which is located in the Gedeo Zone of Ethiopia. The area spans coordinates from 6°31'41"N to 7°30'90"N and 38°18'70"E to 38°19'91"E (see Figure 1). The Gidabo basin is classified as one of the rift valley basins in Southern Ethiopia and includes three regional states: Oromia, Sidama, and the Southern Nations, Nationalities, and Peoples' Region (SNNPR). The basin is drained by numerous intermittent and permanent streams and rivers that originate from the highlands of Gedeo and Sidama. The topography of the basin is predominantly undulating in the upper catchment, while the lower parts feature relatively gentle slopes. The watershed has been under integrated watershed management since 2005, with various conservation and livelihood measures implemented in the area. The main soil conservation practices include soil bunds (SB), micro-basins (MB), and fanya-juu (FJ).

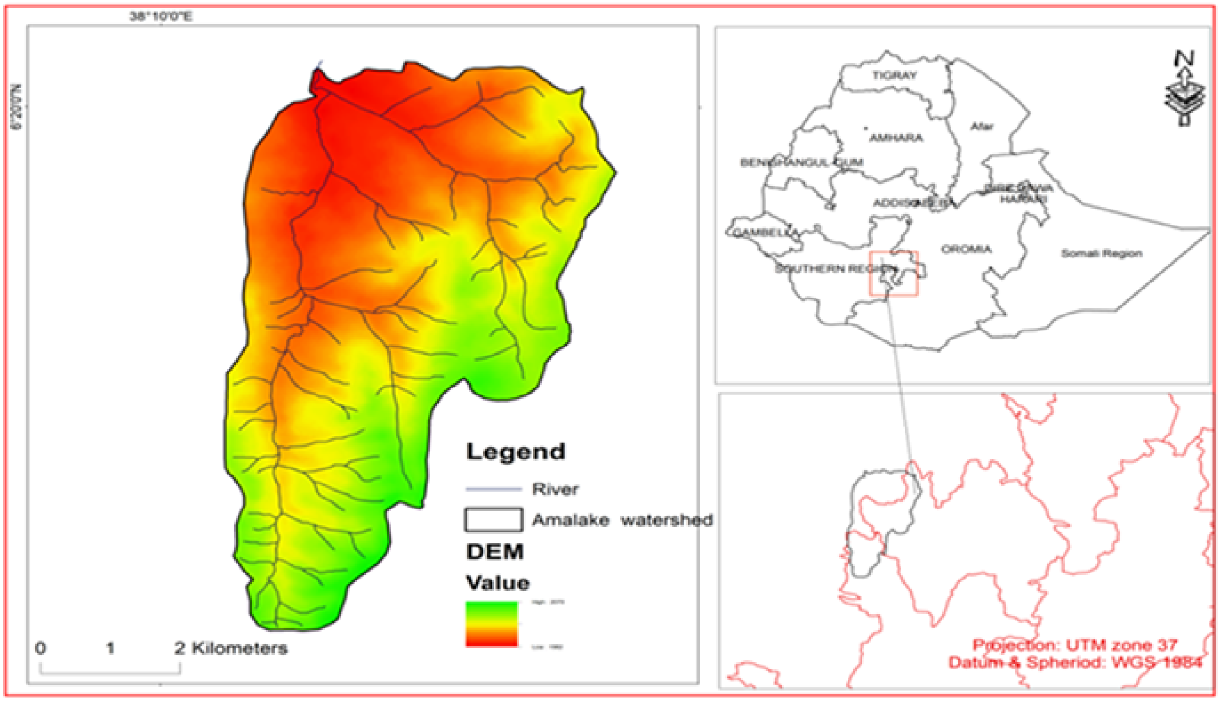

Figure 1. Location Map of the Study Area

Situated at an altitude of approximately 1,975 meters above sea level, the study area experiences a moderate to high average annual temperature and rainfall. The climate is classified as cool sub-humid to humid, which contributes to its significance as one of Ethiopia's prime coffee-growing regions. The average annual rainfall and temperature from 2010 to 2020 are illustrated in Figure 2.

2.2 Sampling strategy

Soil samples were gathered in the summer of 2022. The locations for sampling were intentionally chosen based on three soil conservation methods (soil bunds [SB], micro-basins [MB], and fanya-juu [FJ]) that have been in practice for more than ten years within the watershed. Additionally, the sampling sites were stratified according to land slope gradients (upper: 3%, middle: 6%, and lower: 5%), with samples collected from each slope category in the landscape. Soil samples were collected from depths of 0-35 cm in areas under each soil management practice, as well as from control sites.

In total, thirty triplicate composite soil samples (5 kg each) were collected from the sampling areas, all sourced from uncultivated lands to determine soil attributes, with particular focus on major soil quality indicators (SQIs). The collected soil samples were placed into sampling bags and conveyed to the Chemistry Laboratory at Dilla University. After air-drying, portions of the soils were ground to different particle sizes for various analyses. The prepared samples were preserved in labeled bags for assessments of soil physicochemical and biological characteristics. For bulk density (BD) measurements, core samples were collected using sample corer cylinders.

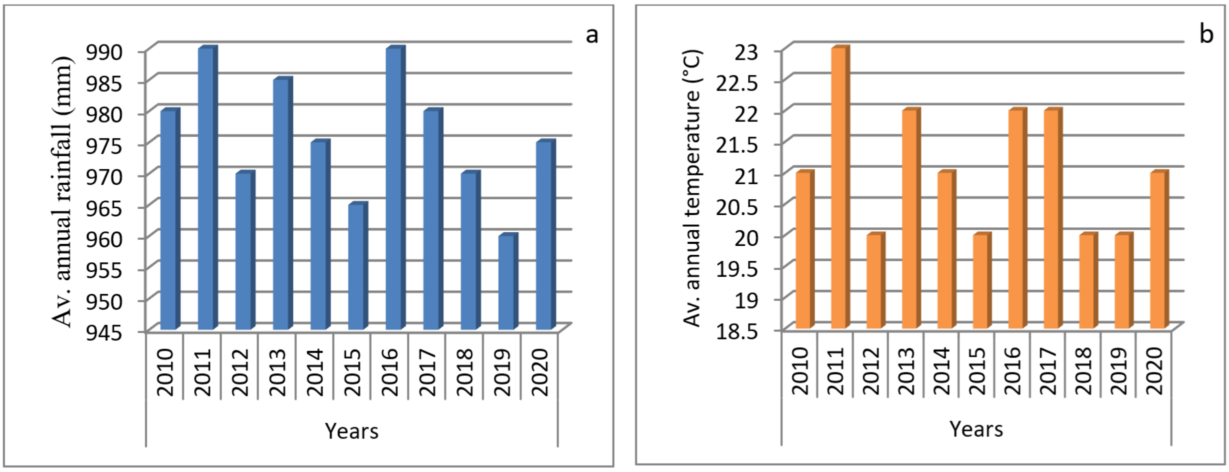

Figure 2. Average annual rainfall (a) and average annual temperature (b): source World Weather Online : https://www.worldweatheronline.com/dilla-weather-averages/et.aspx (Accessed 10/09/2024)

2.3 Instruments, Chemicals and Reagents

Analytical grade chemicals were used for all analyses, including concentrated H_2SO_4, saturated H_3BO_3, sodium hydroxide ($NaOH$) at 10 N, and a mixture ofK_2SO_4, $CUSO_4{\cdot}5H_2O$, and Se (in a 100:10:1 w/w ratio) for nitrogen determination using the Kjeldahl procedure. Ammonium acetate solution (1 N NH_4OAc) was used for the extraction of Ca, Mg, and K, while 0.005 M DTPA (diethylene triamine pentaacetic acid), 6 N hydrochloric acid (HCl), 0.1 M TEA (triethanolamine), and 0.1 M $CaCl_2$ (calcium chloride) were used for extracting micronutrient cations (Fe, Zn, Mn, Cu). A $HNO_2 - HClO_4$ diacid mixture was employed for digesting samples for micronutrient determination, and 2% $NaCN$ (sodium cyanide) was added to prevent interference of Fe, Zn, Mn, and Cu while measuring Ca and Mg using Atomic Absorption Spectrophotometry (AAS).

For boron (B) determination, activated charcoal, azomethine-H solution ($C_{17}H_{12}NNaO_8S_2$), hydrochloric acid (HCl) at 0.05 N, and a 0.4 N $K_2Cr_2O_7$ solution were used, along with a (2:1) mixture of H_2SO_4 and H_2PO_4, mercury (II) oxide (HgO), phenanthroline indicator, and 0.2 N ferrous ammonium sulfate for carbon determination. Standard stock solutions of all elements were prepared to develop calibration curves for each element.

In terms of instrumentation, an Atomic Absorption Spectrophotometer (AAS) was used to determine Ca, Mg, Fe, Zn, Mn, Cu, and Mo; a flame photometer (FAAS) was used for K determination; a UV-Vis spectrophotometer was employed for B and P determination; and an automatic titrator connected to a pH meter, along with a vortex tube stirrer, was used for extraction and digestion procedures.

2.4 Analysis of the Soils Physicochemical Properties

Selected soil physicochemical and biological attributes for soil quality (SQ) assessment were investigated following their respective standard methods. For soil physical attributes, five main physical indicators of SQ were selected: soil texture (ST), bulk density (BD), aggregate stability (AS), total porosity (TP), and water retention capacity (WRC). Particle size distributions (soil textural classes) were measured using a Bouyoucos hydrometer (Bouyoucos, 1962). Bulk density was measured according to the method described by Dexter (2004). Aggregate stability was assessed using the method outlined by Le Bissonnais (1996). Total porosity was determined following the procedure reported by Brady and Weil (1996), and water retention capacity was measured using the method indicated by Ghanbarlan *et al*. (2010).

Regarding soil chemical attributes, six main chemical indicators of SQ were selected: soil pH, carbonate content, cation exchange capacity (CEC), exchangeable acidity (EA), plant nutrient availability, and toxic elements content. Soil pH was assessed using a pH meter equipped with a combined glass electrode in a soil/water (1:2) suspension (referred to as pHw) and in a soil/0.01 M $CaCl_2$ (1:2) suspension (designated as p$HCaCl_2$). The cation exchange capacity (CEC) of the soils was evaluated through the ammonium acetate method. Electrical conductivity (EC) was recorded in accordance with the procedures outlined by Rowell (Van Reeuwijk, 1992). To determine plant nutrient availability, the available form of phosphorus (P) was measured utilizing the Bray I method. The analysis of plant macronutrients, including sodium (Na) and potassium (K), was conducted using flame atomic absorption spectrophotometry (FAAS), whereas calcium (Ca), magnesium (Mg), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were analyzed through atomic absorption spectrophotometry (AAS) following extraction with 1 N ammonium acetate (NH_4OAc at pH 7).

For the investigation of soil biological attributes, total nitrogen (TN), organic matter (OM), carbon-to-nitrogen ratio (C/N), enzyme activity (specifically soil glomalin), and bioavailability of contaminants were selected as major indicators of soil quality. Organic matter was determined using the Walkley-Black method, while plant-available forms of contaminants such as aluminum (Al), lead (Pb), nickel (Ni), and chromium (Cr) were measured following their respective standard methods.

2.5 Determination of SQI

To identify the most critical soil characteristics for assessing soil quality (SQ), principal component analysis (PCA) was utilized to establish the Soil Quality Index (SQI) and to eliminate less significant attributes. This analytical method enabled the selection of relevant variables while discarding redundant ones (Mandal *et al.*, 2011; Selmy *et al.*, 2021). Subsequently, the weights of each variable were evaluated and validated for inclusion in the SQI calculation. A number of essential soil physical and chemical indicators—including bulk density (BD), cation exchange capacity (CEC), moisture content (MC), water-stable aggregates (WSA), pH, soil organic matter (SOM), total nitrogen (TN), plant availability (PA), K^+, Ca^{2+}, Mg^{2+}, Fe^{2+}, Zn^{2+}, Mn^{2+}, and Cu^{2+}—were assessed for each soil sample to conduct the PCA.

Among the total dataset, characters with high load factors were identified as the principal components of the analysis. To decide which of these multiple variables would be included in the SQI determination, a correlation analysis was conducted. If the correlation between variables was too high, those variables were excluded from the SQI calculation. Conversely, if the correlation among high load factors was low, it indicated that each of those variables was important, and all were retained for SQI determination. Ultimately, a weighted additive method was used to calculate the SQI. The final SQI equation utilized in the PCA is provided below.

$$SQI = \sum_{i=1}^{n} (W_i \, x \, S_i)$$

Where W_i is the weighting factor of the variables obtained from the PCA computed, S_i is the score of variable, and n is the number of selected variables.

2.6 Data Analysis

The analyses performed in this research utilized SPSS Statistics 20.0 software alongside Microsoft Excel. A one-way analysis of variance (ANOVA) was implemented to evaluate the levels of variation among the different calculated means. Individual means were distinguished using Duncan's new multiple range test, with a significance threshold established at $p < 0.01$. Principal component analysis (PCA) was utilized to determine the index weight of each soil quality indicator.

3 Results and Discussion

3.1 Changes of Important Soil Physicochemical Characteristics

The dynamic alterations in the physicochemical properties of soil are depicted in Figure 3, which encompasses bulk density (BD), water-stable aggregates (WSA), soil moisture content (SM), cation exchange capacity (CEC), soil pH, and soil organic matter (SOM) across the four watershed management practices and various land slopes. The plots in the figure were created using polynomial fitting, with the attributes of control soil samples (those that received no management practices) serving as starting points.

A significant reduction in soil bulk density was observed across all three management practices compared to the control (Figure 3A). The reductions were 26.67% to 28.57% under soil bund (SB), 11.76% to 21.43% under micro-basin (MB), and 5.56% to 14.29% under fanya-juu (FJ). This indicates that these practices can effectively optimize soil bulk density, with SB being the most effective conservation practice. These results clearly demonstrate that implementing any of these conservation practices can alleviate soil compaction and optimize bulk density. The superior performance of SB is likely due to its more permanent physical structure, which provides robust, long-term protection against compaction forces.

The data for water-stable aggregates (WSA) revealed considerable variation across different land slopes under the management practices (Figure 3B). The highest WSA value of 74.35% was recorded in soils under SB on the lower slope, while the lowest value of 40.30% was found in untreated soils (with no management practices) on the middle slope. This stark contrast can primarily be attributed to the differential input of organic matter. Managed sites, particularly those with higher vegetation cover, benefit from increased organic matter inputs, which act as a binding agent, enhancing soil structural stability by cementing soil particles into stable aggregates and reducing susceptibility to erosion. This interpretation is supported by findings from Bezabih *et al.* (2016) and is consistent with other studies (Liu *et al.*, 2020; Olorunfemi *et al.*, 2018), which also reported significantly decreased WSA in unmanaged lands.

A statistically significant difference ($p < 0.01$) was confirmed between the WSA values of managed soils and those from control plots (App. Table 1), which were subject to communal grazing. The physical disturbance caused by animal trampling and overgrazing in the control plots mechanically breaks apart soil aggregates. Coupled with low organic matter input due to reduced plant biomass, this leads to severe degradation of soil structure, as previously documented by Kindu *et al.* (2016). Quantitatively, the three management practices increased WSA on the upper slope by 65.07% (SB), 47.68% (MB), and 32.83% (FJ), respectively. Consistent with the bulk density results, SB demonstrated the greatest positive impact on improving aggregate stability across all slope positions.

Soil moisture content (MC) under the different practices across the topographic gradient is presented in Figure 3C. The highest MC value of 14.48% was measured in soils under SB on the lower slope. In this ecosystem, as in most others, the soil water balance is governed by inputs from rainfall and outputs through infiltration, surface runoff, base flow, and evapotranspiration (Rockström *et al.*, 2010; Jaafarzadeh and Vayskarami, 2022). The SB practice excels in moisture conservation by effectively controlling surface runoff, allowing more water to infiltrate and be stored in the soil profile. Additionally, the denser vegetation cover typically found on lower slopes helps minimize moisture loss by reducing soil evaporation and providing shade. The combination of these factors explains why the SB practice on the lower slope retained the highest moisture content, aligning with findings from Lin *et al.* (2018).

Moreover, other soil conservation methods have also led to a significant enhancement in moisture content (MC) when compared to soils that did not undergo conservation practices (App. Table 1). In general, the water balance within the region is predominantly affected by the soil management techniques that are applied. This underscores the importance of choosing and executing suitable soil management practices to improve soil moisture, which serves as a crucial connection between biogeochemical and hydrological processes, facilitating interactions among the soil environment, vegetation cover, and climate change. Consequently, it is essential to sustain the ecosystem's water balance, which can be achieved by increasing the soil's water-holding capacity through appropriate soil management practices, thereby improving soil moisture content (Francaviglia *et al.*, 2023; Ghimire *et al.*, 2023).

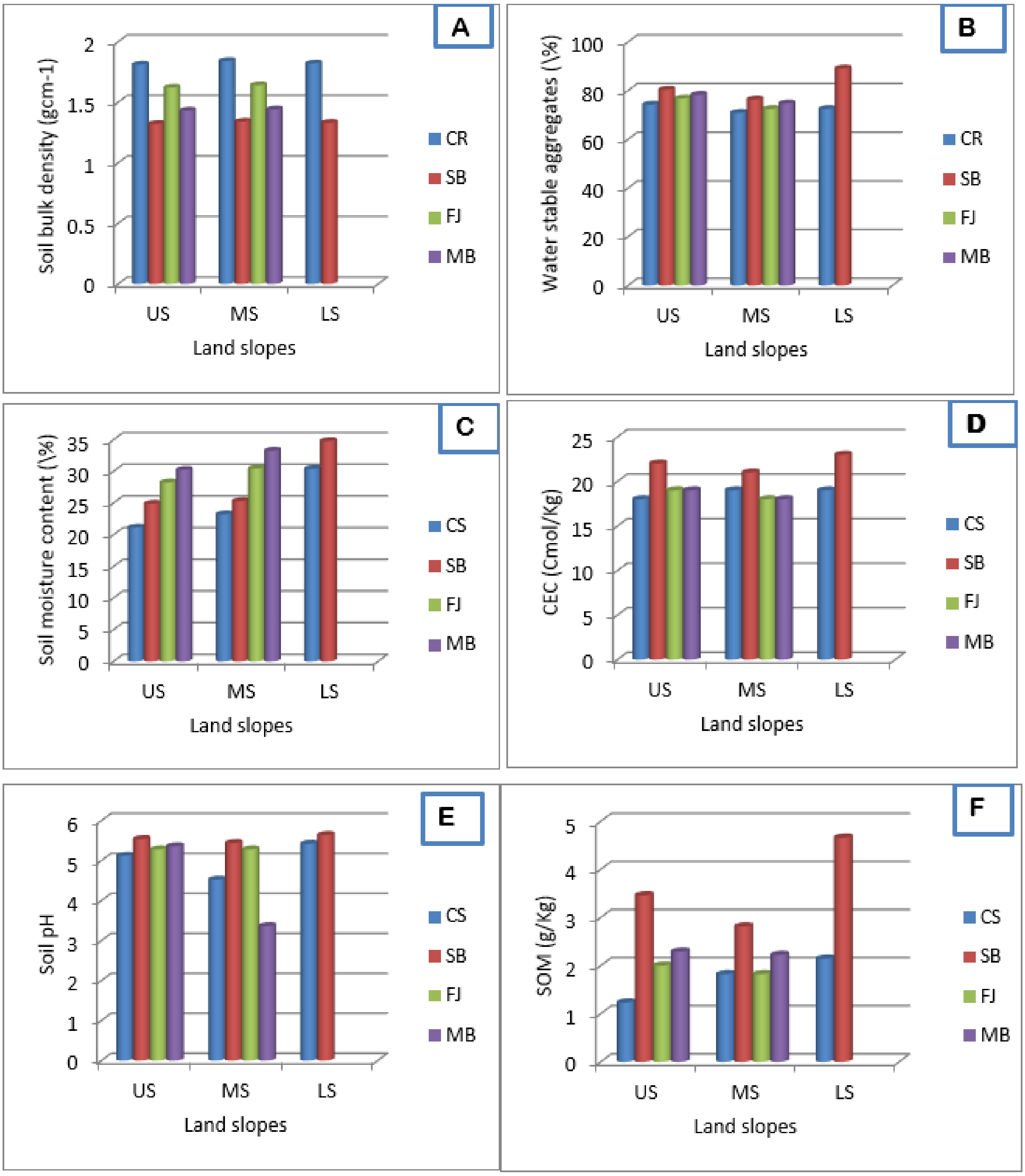

Figure 3. Changes of soil physicochemical properties: bulk density (A), water stable aggregates (B), soil moisture contents (C), cation exchange capacity (D), soil pH (E), and soil organic matter (F)
US = Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro-basin

The change in cation exchange capacity (CEC) closely followed that of soil organic matter (SOM), with the highest CEC value (23 cmol kg^{-1}) observed under soil bund (SB) management in the lower slope (Figure 3D). This relationship is due to the direct correlation between CEC and SOM; any soil management practice that significantly improves SOM also enhances CEC. Additionally, the soil under SB management exhibited the highest CEC across all land slopes, indicating that CEC, which is crucial for nutrient storage capacity, can be improved by employing SB management practices in soils with similar slopes.

As shown in Figure 3E, soil pH levels were slightly improved by other management practices, though they did not reach optimal values. Variations in soil pH were noted not only across different management practices but also among land slopes, likely due to varying degrees of basic cation leaching by rainfall.

Soil organic matter (SOM) content increased with watershed management, with the highest value (4.66 g kg^{-1}) found in soils under SB management in the lower slope (Figure 3F). This increase can be attributed to the relatively low slope angle and higher vegetation cover in the lower slope, which serve as sources of SOM. Generally, SOM contents were highest in soils under SB management in the lower slope compared to other practices across all slopes. Under SB management, SOM contents increased by 100%, 54.39%, and 100% compared to control samples in the upper slope (US), middle slope (MS), and lower slope (LS), respectively. These percentage increments were greater than those observed for FJ and MB management practices, indicating that SB has a relatively higher impact on improving SOM in this soil type and slope.

Soil nitrogen content mirrored the changes in SOM across all land slopes and management practices, although the observed changes were minimal compared to SOM. Similar findings were reported by Lei *et al.* (2016), who noted significant changes in nitrogen content after several years of soil management. Variations in available phosphorus (PA) and available micronutrient contents were primarily related to soil pH levels, highlighting the importance of pH as a parameter for assessing soil health, particularly in degraded soils. Therefore, employing appropriate land management practices to optimize soil pH can significantly influence crucial soil dynamics. In this study, optimal pH values (6–7) for healthy plant growth were observed under SB management across all land slopes.

Phosphorus contents in soils under the three management practices were significantly higher than in soils without management practices. The highest phosphorus value (382 mg kg^{-1}) was observed in soils under SB, while the lowest (234 mg kg^{-1}) was found in soils under FJ in the upper slope. Similar to SOM, nitrogen, and CEC, this study confirms that SB is the most effective soil management practice for these soil types and landscapes. Regarding land slope, the highest phosphorus content was observed in the upper slope, likely due to the less soluble nature of phosphorus compounds, which restricts nutrient leaching to lower slopes. This suggests a higher shortage of phosphorus in the upper slope, which is less prone to dissolution and leaching. Thus, it can be concluded that degraded soils with significant phosphorus accumulation can be managed to become good sources of available phosphorus for healthy and productive plant growth. This underscores the need to employ ecology-specific effective land management practices that enhance phosphorus availability.

3.2 Dynamic Changes of Nutrient Availability under Different Soil Managements

As shown in Figure 4 (A, B, C), the available macronutrient contents (Ca^{2+}, Mg^{2+}, and K^{+}) significantly increased under the three land management practices compared to the control sample. The highest values recorded were 3.64, 1.98, and 0.78 cmolc kg^{-1} for Ca^{2+}, Mg^{2+}, and K^{+}, respectively, in the lower slope under soil bund (SB) management. This increase can be attributed to the readily soluble properties of the nutrient-containing compounds, which facilitate leaching down the slope, as well as the relatively higher capacity of SB management to restrict further nutrient leaching. Therefore, this research indicates that to minimize the leaching of K^{+}, Ca^{2+}, and Mg^{2+} and improve their availability to plants, SB is the best soil management practice for this type of landscape and soil.

Micronutrient availability was also significantly affected by the soil management practices (Figure 4 D, E, F). As previously discussed, these practices impact soil properties such as pH, SOM, CEC, and moisture content (MC), which in turn determine the dynamics and transformations of micronutrients in the soil. SOM is particularly important as it influences various physicochemical reactions that affect micronutrient availability. It promotes a reduced (lower redox potential) environment, enhancing the availability of micronutrient cations in the soil.

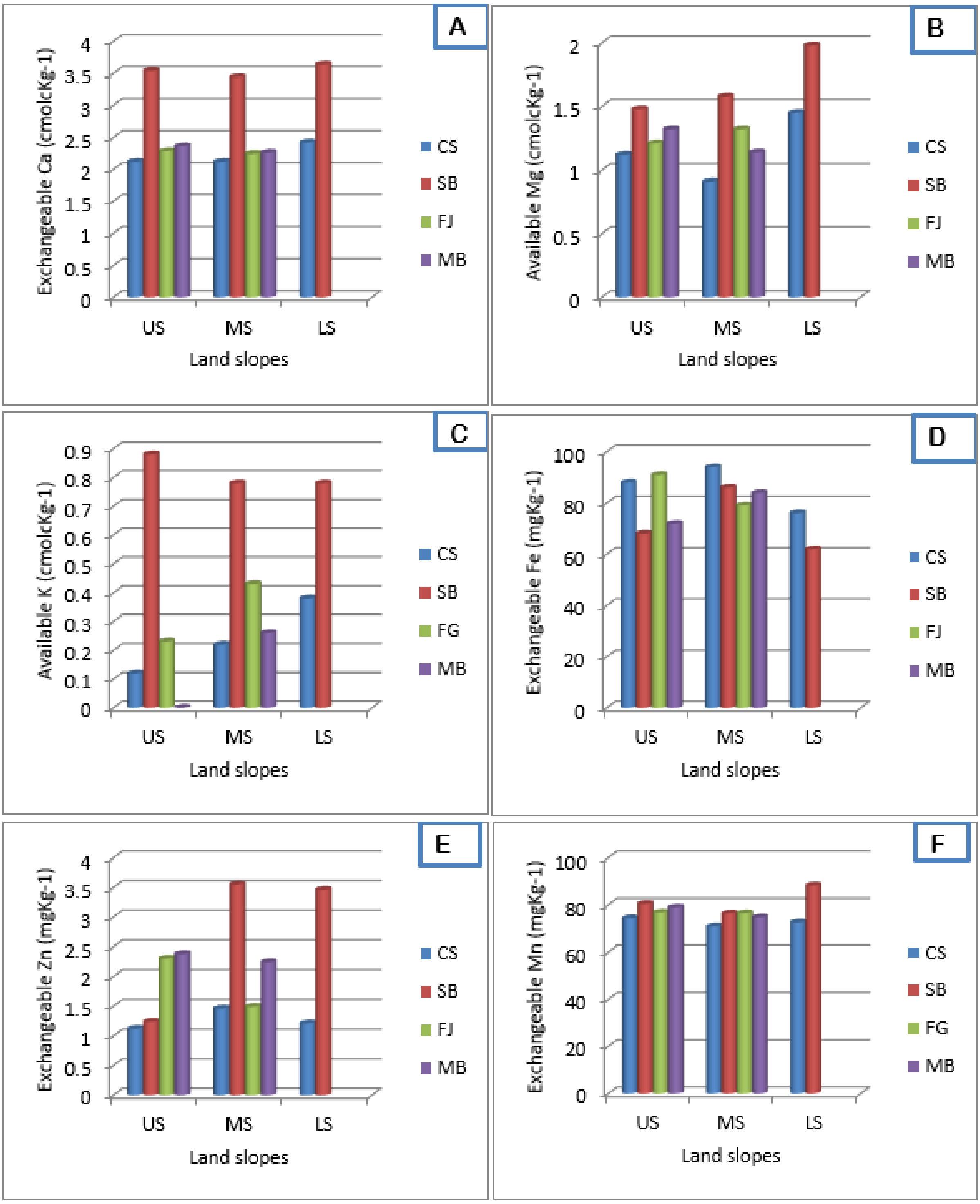

Figure 4. Nutrients dynamics under different soil conservation practices and land slop US – Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin

The complexation of micronutrients with carbon compounds occurs under reduced conditions, and an increased SOM content in the soil transforms adsorbed micronutrient fractions into more plant-available forms.

Moreover, any soil management practice that increases soil moisture content enhances the water-soluble and exchangeable forms of micronutrients, further facilitating their uptake by plants. This underscores the importance of soil management practices that improve SOM, MC, and optimize pH levels to enhance micronutrient availability. In this study, SB produced the highest content of available micronutrients across the three land slopes. Therefore, for watersheds with similar soil types and landscapes, SB can be recommended as an effective soil management practice to enhance micronutrient availability.

In summary, the findings of this study suggest that suitable soil conservation methods that improve soil quality indicators (SQI), including aggregate stability (AS) and water retention capacity (WRC), represent viable solutions for sustaining soil moisture and decreasing water requirements in the face of changing climate conditions. Moreover, the effective application of soil moisture conservation strategies aids in reducing runoff rates, rapid infiltration, base flow, and nutrient losses, while simultaneously increasing soil moisture and nutrient accessibility for plant development.

Increasing land productivity and crop production is crucial, and several researchers have argued that effectively measuring soil quality indicators (SQI) can provide a valuable basis for identifying and implementing effective soil conservation measures (Van Leeuwen *et al*., 2015; Sánchez-Navarro *et al*., 2016; Francaviglia *et al*., 2023).

3.3 Soil Quality Index Measurements

n this research, principal component analysis (PCA) was applied to the soil properties to compute the parameters for the final Soil Quality Index (SQI) (Figure 5). Eight soil indicators that showed no significant correlation were identified, each with a corresponding weight. These indicators included pH, cation exchange capacity (CEC), soil organic matter (SOM), total nitrogen (TN), phosphorus (P), bulk density (BD), moisture content (MC), and water-stable aggregates (WSA). This study demonstrated that these soil indicators are valuable for assessing the SQI of soils under similar management practices. The SQI equation was used to calculate the SQI for soils across different management practices and land slopes. As shown in Figure 3, the SQI values of soils under various management practices were significantly different.

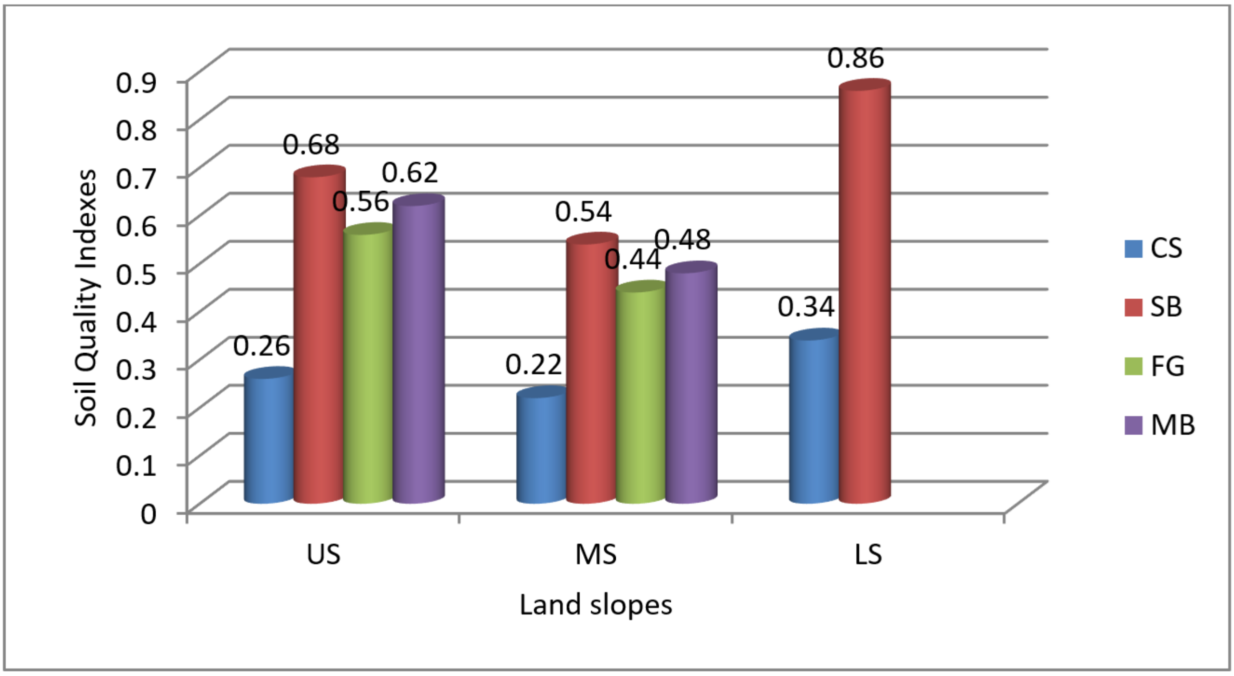

Figure 5. Soil quality indexes as impacted by soil conservation practices US – Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin

This observation aligns with several studies (Dang *et al*., 2020; Liu *et al*., 2020) that demonstrate significant differences in Soil Quality Index (SQI) values among soils under different management practices. The dynamic changes in SQIs with varying management practices and land slopes indicate that soil quality indicators were differentially impacted by these practices. Relatively higher SQI values of 0.68, 0.54, and 0.86 were recorded in the upper slope (US), middle slope (MS), and lower slope (LS), respectively, for soils under the soil bund (SB) management practice. This suggests that to enhance SQI, it is essential to select appropriate soil management practices, and this study indicates that SB is the most effective method for improving SQI in soils of the same type and similar ecosystem.

4 Conclusions

This study provides a comprehensive, data-driven evaluation of the long-term efficacy of three common soil conservation practices—soil bund (SB), micro-basin (MB), and fanya-juu (FJ)—in enhancing soil quality and nutrient cycling in the degraded landscapes of the Amalake watershed, Ethiopia. The findings clearly demonstrate that the implementation of soil conservation structures induces significant positive changes in key soil physicochemical properties, with the SB technique emerging as the most effective intervention.

The superiority of SB was evident across a wide range of critical soil health indicators. It achieved the most substantial improvements in reducing soil bulk density, enhancing water-stable aggregates, increasing soil moisture content, and boosting soil organic matter. Additionally, SB was the most effective practice for improving the soil's nutrient retention capacity, as reflected in the highest cation exchange capacity (CEC), and it led to the greatest increases in available macronutrients (Ca^{2+}, Mg^{2+}, K^{+}).

The calculated Soil Quality Index (SQI) quantitatively synthesized these benefits, confirming that SB yielded the highest soil quality scores across all landscape positions, with maximum impact on the lower slope. A critical finding is the demonstrable interaction between conservation practice efficacy and landscape topography, underscoring the need for context-specific management strategies. The consistent performance ranking of the soil conservation practices—SB > MB > FJ > Control—provides a clear hierarchy for farmers and policymakers to prioritize interventions.

Therefore, to effectively reverse land degradation, enhance nutrient cycling, and build resilient agricultural systems in this ecology and similar regions with steep slopes, the widespread promotion and implementation of soil bunds is strongly recommended. This research establishes a validated SQI framework that can be reliably used for future monitoring and assessment, offering a powerful tool for evidence-based land management policies and practices aimed at achieving long-term environmental sustainability.

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Conflict of Interests

The authors have no conflict of interests to declare.

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Appendices

Table 1. Soil indicators used to estimate soil quality index (SQI)

Slope	WSMT	Soil Quality Indicators											
		pH	BD (gcm^{-3})	MC (%)	CEC ($Cmol.kg^{-1}$)	EC (μScm^{-1})	WSA (%)	Poro. (%)	EA ($Cmol.kg^{-1}$)	PT (mg/Kg)	SOC (g/Kg)	NT (%)	SOM
US	CS	5.12	1.8	21.1	18	143.13	74.2	30.2	8.21	132	2.02	0.12	1.23
	SB	5.54	1.4	24.9	22	167.24	80.3	34.3	6.1	382	2.84	0.26	3.46
	FJ	5.28	1.6	28.2	19	152.3	76.7	40.9	7.43	234	2.21	0.21	2
	MB	5.36	1.5	30.2	19	158.38	78.2	47.2	6.81	242	2.43	0.16	2.29
MS	CS	4.52	1.9	23.2	17	134.46	70.8	33.4	8.11	121	2	0.12	1.82
	SB	5.44	1.5	25.3	21	184.55	76.3	37.2	6.82	352	2.88	.0.24	2.81
	FJ	5.28	1.8	30.4	18	169.49	72.4	43	7.82	263	2.46	0.22	1.82
	MB	5.36	1.7	33.3	18	179.24	74.7	47.3	7.22	326	2.62	0.18	2.22
LS	CS	5.42	1.8	30.4	19	130.21	72.4	36.7	7.82	145	2.42	0.23	2.14
	SB	5.64	1.4	34.8	23	186.46	89	48.5	5.42	256	2.89	0.28	4.66
CV		0.56	1.5	0.53	1.63	0.844	0.13	0.9	1.87	1.864	1.831	1.11	1.11
LSD		0.02	0.012	0.02	0.018	0.018	0.02	0.02	0.018	0.015	0.019	0.02	0.02
R^2		0.98	0.998	1	0.969	0.998	0.98	1	0.988	0.974	0.988	1	0.98
F-t		**	**	**	**	**	**	**	**	**	**	**	ns

US – Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin, WSMT = Watershed management type, BD = Bulk density; MC = Moisture content; CEC = Cation exchange capacity; EC = Electrical conductivity; WSA = Water stable aggregates, Poro. = Porosity, EA = Exchangeable acidity; SOC = Soil organic carbon; PT = Total phosphorus, NT = Total nitrogen; CV = Coefficient of variance; LSD = Least significance difference; ** = Significant at $p \leq 0.01$, ns = not significant. Means within a column with the same letters are not significantly different.

Table 2. Soil macronutrient and micronutrients contents under the watershed management

Slope	WSMT	Exchangeable macronutrient (cmolc.Kg^{-1})			Mehlich III Extractible Micronutriments (mg.Kg^{-1})					AP (Bray I)
		Ca^{2+}	Mg^{2+}	K^{+}	Fe	Zn	Mn	Cu	B	(mg.Kg^{-1})
US	CS	2.12h	1.12	0.12	88	1.23	74.2	0.22	0.1	1.12
	SB	3.54b	1.48	0.88	68	1.24	80.4	1.31	0.3	1.56
	FJ	2.28f	1.21	0.23	91	2.3	76.8	0.94	0.1	1.24
	MB	2.36e	1.32	0.21	72	2.38	78.9	0.16	0.1	1.42
MS	CS	2.12h	0.91	0.22	94	1.46	70.8	0.39	0.2	1.12
	SB	3.44c	1.58	0.78	86	3.55	76.4	0.21	0.2	1.52
	FJ	2.24g	1.32	0.43	79	1.49	76.4	0	0.1	1.33
	MB	2.26f	1.14	0.26	84	2.24	74.6	0.34	0.1	1.36
LS	CS	2.42d	1.45	0.38	76	1.21	72.5	0.07	0.1	1.15
	SB	3.64a	1.98	0.78	62	3.46	88.2	1.48	1.5	1.82
CV		0.555	1.5	0.525	1.63	0.84	0.13	0.9		
LSD		0.016	0.012	0.015	0.02	0.02	0.02	0.02		
R^2		0.976	0.998	0.996	0.97	1	0.98	1		
F-t		**	**	**	**	**	**	**		

NB: CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin, WSMT = Watershed management practices, AP = Available phosphorus, CV = Coefficient of variance; LSD = Least significance difference; ** = Significant at $p \leq 0.01$, ns = not significant. Means within a column with the same letters are not significantly different.