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Effects of Watershed Management Practices on Glomalin Related Soil Protein as Rapid Soil Health Indicator: The Case of Amalake Watershed, Gidabo Sub-Basin, South Ethiopia

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Abstract

Finding the best tactics suited to particular ecological situations requires a comprehensive grasp of the long-term impacts of watershed management techniques. Tracking trends in changes to soil biogeochemical properties is particularly useful. The purpose of this study was to look into the long-term effects on soil glomalin and associated soil physicochemical parameters of three different watershed management techniques: soil bund (SB), micro-basin (MB), and fanya-juu (FJ). Easily extractable and total glomalin were extracted following standard methods. The study analyzed the impacts of these soil management practices and the correlations between soil glomalin and other soil physicochemical properties. All three soil and water conservation practices resulted in significant changes ($p < 0.05$) in easily extractable glomalin and total glomalin. Notably, the SB management practice produced the highest increase (21.13%) compared to the control sample. The most substantial change (38.26%) in aggregate stability was observed for large macro-aggregates in the lower slope under SB management. Soils under SB in the lower slope had the highest percentage of water-stable aggregates (WSA), 74.35%. The increases were 57.06% to 100% for SB, 72.05% to 77.69% for MB, and 34.16% to 71.90% for FJ in terms of soil organic carbon (SOC) linked to macro-aggregates. The results indicate that all three soil and water conservation practices significantly improved soil physicochemical properties. The decreasing order of changes in soil glomalin, aggregate size distribution, WSA, and nutrient availability was SB > MB > FJ > control sample. This implies that SB is the most effective soil and water conservation practice in semi-humid regions and plateau landscapes.

Keywords/Phrases: Aggregate-associated carbon, Aggregate stability, Soil conservation, Soil glomalin, Soil organic carbon

1 Introduction

In today's context, the rapidly increasing population in Ethiopia necessitates the continuous cultivation of all types of land for food security (Diriba *et al.*, 2020). This demand is exacerbating land degradation in several regions of the country, particularly in the southern parts of the Amalake watershed, which have experienced severe soil degradation. Community-based watershed management (WSM) techniques have been used since 2005 to address this problem and stop the deterioration process (Negasa *et al.*, 2017).

The primary watershed management practices in the area include soil bunds (SB), fanya-juu (FJ), micro-basins (MB), and area exclosures. These practices aim to protect against soil erosion caused by runoff, sheet erosion, and overflow. Area exclosures are specifically used to control unplanned cutting of trees and grass for various uses. These WSM techniques are successful in reducing soil erosion and reestablishing natural vegetation, according to observations (Kindu *et al.*, 2016; Teferi *et al.*, 2016; Giller *et al.*, 2021).

Studying all significant soil parameters is crucial to comprehending the comprehensive effects of soil management techniques on soil quality and health. Soil pH, proteins and enzymes like glomalin, cation exchange capacity, electrical conductivity, and organic matter are important factors that influence soil reactions. These properties significantly influence the soil's capacity to support productive and healthy plant growth. Therefore, investigating the long-term effects of soil management practices on these crucial soil properties is vital.

The persistence of glomalin, which has a carbon content of about 37% and a nitrogen content of 4%, ranges from several months to years (Tchameni *et al.*, 2013). Because of its endurance, glomalin can significantly lower atmospheric carbon dioxide concentrations. Zhu *et al.* (2017) investigated the function of glomalin in ecosystems and the impact of land use on its stability and content. They discovered that glomalin may be used as a criterion for designing agricultural management techniques and an efficient indicator of soil quality.

The presence of soil glomalin is crucial for ecosystem processes, contributing to improvements in soil porosity, water infiltration, root system development, increased soil organic carbon, and erosion resistance (Vicente, 2016). Soil glomalin can be mediated by various stabilizing agents, including soil organic matter, plant roots, soil microbial communities, and their metabolic products (Wang *et al.*, 2018; Diriba *et al.*, 2020).

Watershed management practices also affect soil aggregate stability, a physical property that measures the soil's ability to withstand environmental disturbances (Jia *et al.*, 2016). Increased soil aggregate stability enhances the soil's water-holding capacity and reduces susceptibility to erosion (Wu *et al.*, 2021). The degree of soil aggregate stability serves as an indicator of soil organic matter content, soil reaction, and nutrient cycling (Zhang *et al.*, 2014). Therefore, any soil management practice that affects soil aggregate stability also influences these essential soil properties that underpin ecosystem functioning. Improved soil aggregate stability promotes vegetation restoration and growth (Wu *et al.*, 2021). Stable aggregates, which are formed by glomalin, are more resistant to erosion (Xie *et al.*, 2015). Furthermore, glomalin, which contains 30–40% carbon, is a source of active soil organic carbon (Singh *et al.*, 2021). According to Teferi *et al.* (2016), WSM practices that incorporate biological and physical conservation techniques improve soil stability against erosion and lessen land degradation.

A comprehensive understanding of WSM practices is crucial for prescribing effective management strategies within limited resources. Measuring soil glomalin and aggregate stability can help assess the impact of WSM practices (Zhu *et al.*, 2017). Prior research in the Amalake watershed has mostly concentrated on how land degradation affects the physical characteristics of the soil and the recovery of plants (Negassa *et al.*, 2017). However, there hasn't been much research done on how WSM practices affect aggregate stability and soil glomalin. Therefore, the purpose of this study is to examine how soil management techniques affect the Amalake watershed's glomalin-related protein, soil aggregate stability, and soil organic carbon.

2 Materials and Methods

2.1 Description of the Study Area

The Gidabo basin, which is part of the Amalake watershed, is where this project was carried out. One of the rift valley basins in Southern Ethiopia is the Gidabo basin (Figure 1). It is drained by a number of permanent and sporadic rivers and streams that come from the Sidama and Gedeo highlands. The basin's topography is predominantly undulating in its upper catchment, while the lower parts feature relatively gentle slopes. Agro-ecologically, the basin includes Wurch, Dega, Woina Dega, and Kola regions. Parts of this watershed have been under integrated watershed management since 2005, with various conservation and livelihood measures implemented in the area.

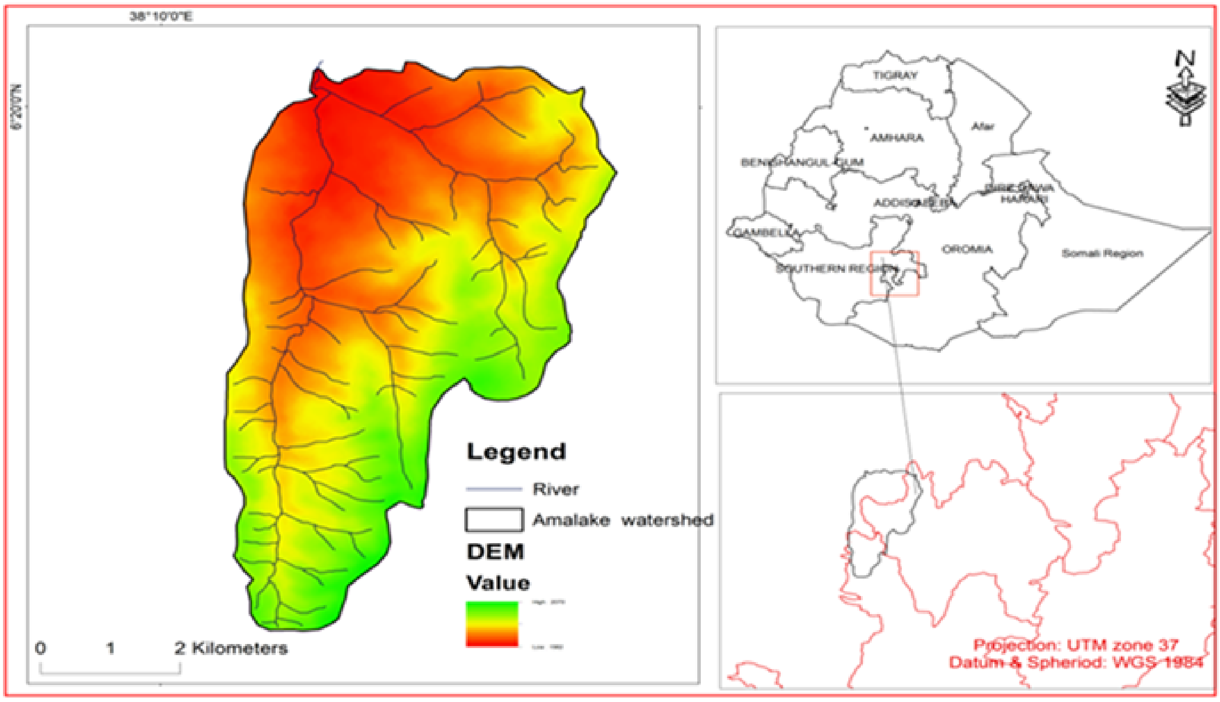

Figure 1. Location map of Amalake Watershed

2.2 Sampling technique and sample size

Along the land slopes—upper slope (US), middle slope (MS), and lower slope (LS)—three typical locations with comparable topography were chosen. Each site used one of three watershed management techniques: soil bund (SB), fanya-juu (FJ), and soil micro-basin (MB). The total area of the watershed is approximately 65 hectares. Triplicate soil samples were taken from each WSM practice at each slope using an auger soil sampler at a depth of 0–30 cm using a random grid sampling technique.

A control sample from lands without WSM practices was also included. In total, 36 samples were planned for collection; however, only one watershed management practice was present on the lower slope, resulting in a total of 30 samples collected. These included triplicate samples from areas of US-SB, US-FJ, US-MB, MS-SB, MS-FJ, MS-MB, and LS-SB, along with the control samples. For further analysis, the gathered soil samples were shipped to the Dilla University Chemistry Laboratory in regular plastic sampling bags.

2.3 Extraction and determination of glomalin related soil proteins

The technique outlined by Wright and Upadhyaya (1996) was used to obtain easily-extractable and total glomalin-related soil protein. To eliminate the readily extractable glomalin (EEG), a three-gram sample of air-dried soil was autoclaved at 121°C for thirty minutes in 24 milliliters of sodium citrate buffer (20 mM, pH 7.0). Following centrifugation at 10,000 rpm, 8 mL of 50 mM citrate (pH 8.0) was added to the residual soil after the supernatant was extracted. To extract total glomalin (TG), this mixture was heated to 121°C for 60 minutes. The red-brown glomalin was eliminated by doing another extraction with 50 mM citrate until the supernatant took on a straw hue. The total protein content of this cleared extract was ascertained by using a tiny subsample in a typical colorimetric protein quantification experiment.

2.4 Aggregate stability determination

The water stability of air-dried aggregates was assessed using the technique outlined by Kemper and Rosenau (1986). To get rid of aggregates in the 1-2 mm and 0.5-1 mm size categories, air-dried bulk soil was sieved. Capillary action was used to pre-wet four grams of aggregates in a sieve. While the 0.5–1 mm aggregates were put in a 0.01 mm sieve, the 1-2 mm aggregates were put in 0.25 mm sieves. The aggregates were pre-wet by capillary action and then tumbled in a water column for five minutes. The leftover aggregates were then dried at 70°C, and the following formula was used to determine aggregate stability:

$$\%AS = [AR(g) - \frac{CM(g)}{4g - CM(g)}]x100 \quad (1)$$

Where, AS = Aggregate stability; AR = aggregate remains on the sieve (g); CM = Coarse materials (g)

2.5 Data analysis

SAS was used for data analysis. To evaluate significant variations in the characteristics among the various slopes and watershed management techniques, ANOVA was utilized. Fisher's least significant difference (LSD) method was used to compare means. Furthermore, connections between glomalin-related proteins, nutrient availability, and soil aggregate stability were investigated using Pearson correlation.

3 Results and Discussion

3.1 Effect of Watershed Management Practices on Soil Glomalin and Related Soil Properties

As shown in Table 1, the soil glomalin content under the different watershed management (WSM) practices indicated that easily extractable glomalin (EEG) was significantly ($p < 0.01$) higher under the soil bund (SB) management compared to the other practices. Micro-basin management also yielded relatively higher EEG values compared to fanya-juu (FJ) and the control sample. Specifically, the EEG in soils under the SB management practice was 21.13%, 17.93%, and 11.72% higher than that in the control sample (CS), FJ, and micro-basin (MB), respectively. Overall, the different WSM practices varied in their impacts on soil glomalin, with the decreasing order of impact being SB > MB > FJ > CS. The highest glomalin content in soils under SB may be attributed to the effective conservation of soil organic matter, which creates a conducive environment for arbuscular mycorrhizal fungi (AMF) to colonize plant roots, as glomalin is produced by these fungi (Chang *et al.*, 2021).

This is in line with research by Wang *et al.* (2020), which shows that areas with higher concentrations of arbuscular mycorrhizal fungus (AMF) have higher glomalin content. Comparing SB to the other watershed management (WSM) techniques and the control sample, total glomalin was also considerably ($p < 0.05$) impacted. Specifically, total glomalin content in soils under SB management was 38.41%, 46.78%, and 52.41% higher than that in soils under micro-basin (MB), fanya-juu (FJ), and control samples (CS), respectively. The comparatively low levels of total glomalin (TG) and easily-extractable glomalin (EEG) in the control samples could be explained by increased erosion rates brought on by rainfall and lower inputs of soil organic matter (SOM). According to other studies (Vicente *et al.*, 2019; He *et al.*, 2020), the population of AMF declines in regions lacking land conservation measures that improve plant cover and SOM input, resulting in decreased soil glomalin. Additionally, soil glomalin content is directly related to soil aggregates that support AMF hyphae. Consequently, in the control samples and soils under less effective WSM practices, such as FJ, the soil glomalin content is diminished. According to other research, a number of factors, including landscape features, affect the amount of glomalin in the soil (Kindu *et al.*, 2016).

Furthermore, it was observed that soil management practices significantly impacting glomalin content, particularly the EEG form, also significantly affected the carbon (C) and nitrogen (N) contents in the soil. The results revealed that EEG content increases with higher levels of C and N in the soil.

This finding agrees with the report by Fokrom *et al.* (2013), which states that soil C and N contents are positively and significantly correlated with soil glomalin (EEG) content. This implies that several soil characteristics are highly positively correlated with soil glomalin, especially the easily extractable form, as also reported by Wang *et al.* (2018).

Table 1. Soil glomalin contents under different WSM practices

WSM Practices	Land Slope and Soil glomalin contents (mg g^{-1})					
	US		MS		LS	
	EEG	TG	EEG	TG	EEG	TG
CS	2.15^j	6.33^g	2.12^j	5.33^h	2.78^i	6.32^g
SB	7.93^b	18.96^b	7.58^c	19.13^b	8.23^a	22.64^a
FJ	4.64^g	9.30^e	4.23^h	8.29^f		
MB	5.75^d	15.33^d	5.31^e	16.34^c		
CV	0.562	0.85	0.664	0.844	0.661	0.848
LSD	0.016	0.012	0.023	0.042	0.023	0.032
R^2	0.976	0.998	0.988	0.977	0.963	0.966
F-t	**	**	**	**	**	**

Means labeled by the same letters down each column are not significantly different

US = Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin, WSM = Watershed management, EEG = easily extractable glomalin, TG = Total glomalin, PA = Available phosphorus, NT = Total nitrogen, CV = Coefficient of variance; LSD = Least significance difference; ** = Significant at $p \leq 0.01$.

3.2 Effect of Watershed Management Practices on Soil Aggregate Size Distribution

In terms of aggregate size distribution, it was found that under all soil management techniques, the proportion of macro-aggregates (> 2 mm) was larger than that of smaller aggregate sizes (Table 2). This result is consistent with the findings of Liu *et al.* (2020), who found that among different land management techniques, big macro-aggregates (> 2 mm) constituted the largest fraction. Among the different soil management practices, the highest value for large macro-aggregates (38.26%) was recorded in the lower slope under soil bund management. Conversely, the lowest value for aggregate sizes between 0.25 and 0.50 mm was found in the upper slope of soils that received no management practice.

Overall, the relative distribution of aggregate sizes may be attributed to the accumulation of high soil organic carbon in the managed soils. It was noted that areas under different management practices experienced higher organic matter input, along with relatively low erosion and runoff. As it decomposes, this organic matter helps to create larger aggregates (Valerie and Ladislav, 2022). Additionally, strong plant root systems in these managed areas significantly enhance soil aggregation. Similar observations by Wang *et al.* (2020) and Cates *et al.* (2016) indicated that higher macro-aggregates were found in managed lands with improved vegetation cover compared to bare land. Furthermore, areas that did not receive soil management practices exhibited significantly lower proportions of aggregate distribution across all size classes.

Across all land slopes, the percentage of macro-aggregates (> 2 mm fraction) was around SB > MB > FJ > CS. This implies that the soil structure of unmanaged fields has been adversely affected by significant leaching and surface runoff. According to reports, the degree of anthropogenic disturbances determines how much soil aggregates are destroyed (Gelaw *et al.*, 2015). This is because places without soil and water conservation methods are more likely to have soil particles removed. Other researchers have also noted that higher proportions of micro-aggregates were found in lands without any soil management practices. For all land slopes in this investigation, the percentage of micro-aggregates (less than 0.25 mm fraction) decreased in the following order: SB > MB > FJ > CS.

Table 2. Aggregate size distribution (%) under different WSM practices

Land Slope	WSM Practices	Aggregate size distribution (%)				
		> 2mm	1 – 2 mm	0.5 – 1 mm	0.25 – 0.5 mm	< 0.25 mm
US	CS	21.15^{i}	16.32^{h}	14.34^{h}	12.47^{j}	24.14^{d}
	SB	37.91^{b}	28.96^{c}	23.35^{c}	18.73^{c}	30.23^{a}
	FJ	24.68^{f}	19.34^{f}	17.36^{f}	14.38^{h}	15.82^{j}
	MB	30.74^{d}	25.33^{e}	20.42^{d}	12.81^{i}	28.29^{b}
MS	CS	22.34^{h}	18.32^{g}	18.29^{e}	16.27^{f}	20.17^{e}
	SB	37.58^{c}	32.13^{b}	28.16^{b}	21.83^{b}	26.15^{c}
	FJ	24.29^{g}	18.29^{g}	18.27^{e}	15.34^{g}	18.92^{f}
	MB	28.31^{e}	26.34^{d}	20.36^{d}	16.34^{e}	24.18^{d}
LS	CS	24.72^{f}	16.32^{h}	16.34^{g}	16.78^{d}	18.24^{i}
	SB	38.26^{a}	32.64^{a}	28.39^{a}	21.46^{a}	31.26^{a}
CV		0.564	0.854	0.544	0.882	0.541
LSD		0.014	0.016	0.012	0.017	0.014
R^2		0.976	0.978	0.966	0.968	0.946
F-t		**	**	**	**	**

Means followed by the same letter down each column are not significantly different

US = Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin, WSM = Watershed management, PA = Available phosphorus, NT = Total nitrogen, CV = Coefficient of variance; LSD = Least significance difference; ** = Significant at $p \leq 0.01$.

3.3 Effect of Watershed Management Practices on Soil Aggregate Stability

The values of water-stable aggregates (WSA) (%) differed among the land slopes under the three soil management techniques (Table 3). The highest percentage of WSA, at 74.35%, was recorded in soils under soil bund (SB) management in the lower slope, while the lowest percentage, at 40.30%, was found in soils without any management practices in the middle slope. This variation could be explained by comparatively larger organic matter inputs, which enhance soil structural stability in regions with a lot of vegetation cover and lessen soil erosion under various management techniques (Dai *et al.*, 2015).

This observation is consistent with research by Liu *et al.* (2020), who found that WSA significantly decreased in areas without any management methods. Given that organic matter improves soil structure development through binding and also reduces soil erosion, this bolsters the claim that increased aggregate stability is linked to organic matter input (Singh, 2022). Significantly ($p < 0.01$) lower percentages of water-stable aggregates were found in soils collected from lands without management practices, which are commonly used for communal grazing. This decrease can be attributed to physical disturbances and low organic matter input, as grazing can disperse soil aggregates (Kindu *et al.*, 2016).

The various soil management practices—SB, microbasin (MB), and fanya-juu (FJ)—implemented on communal grazing lands increased WSA by 65.07%, 47.68%, and 32.83%, respectively, in the upper slope. Notably, the SB management practice had the most significant impact on improving WSA across all three land slopes.

Overall, the decreasing order of soil management practices in their impact on water-stable aggregates (WSA) was SB > MB > FJ. This pattern can be attributed to the greater capacity of managed areas to recover from structural degradation. Additionally, soil management significantly reduces soil erodibility. The higher vegetation cover in these managed areas protects the soil from structural disturbances (Tesfaye *et al.*, 2016).

Table 3. Effect of watershed management practices on aggregate stability

WSM Practices	Land Slope and Aggregate size distribution (%)					
	US		MS		LS	
	WSA (%)	MWD (mm)	WSA (%)	MWD (mm)	WSA (%)	MWD (mm)
CS	41.15^d	0.66^d	40.30^d	0.62^d	48.33^d	0.69^d
SB	67.93^a	0.96^a	63.35^a	0.91^a	74.35^a	0.98^a
FJ	54.66^c	0.80^c	57.36^c	0.82^c		
MB	60.77^b	0.91^b	60.48^b	0.88^b		
CV	0.662	0.653	0.664	0.644	0.669	0.842
LSD	0.024	0.015	0.024	0.022	0.053	0.036
R^2	0.972	0.988	0.982	0.944	0.966	0.982
F-t	**	**	**	**	**	**

Means followed by the same letter down each column are not significantly different

US = Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin, WSM = Watershed management, WSA = Water stable aggregate, MWD = Mean weight diameter, CV = Coefficient of variance; LSD = Least significance difference; ** = Significant at $p \leq 0.01$.

In contrast, grazing lands that have not received any soil management practices experience lower inputs of organic matter and are more susceptible to soil erosion, runoff, and degradation. Grazing disrupts soil structure, exposing organic matter to microbial decomposition and facilitating soil loss through erosion. Overgrazing leads to trampling effects, which decrease aggregate stability and increase bulk density in open grazing lands (Teferi *et al*., 2016; Das *et al*., 2014).

Another measure of aggregate stability is the mean weight diameter (MWD) of aggregates. Similar to the percentage distribution of aggregate sizes, the three soil management practices resulted in significantly higher ($p < 0.05$) MWD across all land slopes compared to areas that had not received any management practices. The order of MWD from highest to lowest was SB > MB > FJ, with all practices showing greater MWD than the control sample. This indicates that higher organic matter input in managed areas can stabilize soil particles through aggregation. Soil management practices that produce higher MWD are crucial, as increased MWD correlates with lower soil erodibility. Furthermore, any soil management practice that enhances organic matter input and retention indirectly increases both WSA percentage and MWD through binding (Wu *et al*., 2021).

The soil management techniques had a substantial ($p < 0.05$) impact on soil organic carbon (SOC) linked to macro-aggregates (> 0.25 mm). On the other hand, across all land slopes, SOC linked to micro-aggregates (< 0.25 mm) did not significantly differ across the three management strategies (Table 4).

Notably, soils under the soil bund (SB) management practice exhibited higher SOC associated with macro-aggregates, with increments of 81.99%, 100%, and 57.06% compared to soils that received no management practices in the upper slope (US), middle slope (MS), and lower slope (LS), respectively.

These results are in line with studies by Vicente *et al.* (2019) and Carrizo *et al.* (2015), which show that soil management techniques that considerably lessen disturbances result in increased SOC levels linked to macro-aggregates.

Overall, the study observed that the three soil management practices—SB, micro-basin (MB), and fanya-juu (FJ)—resulted in increments of 57.06% to 100%, 72.05% to 77.69%, and 34.16% to 71.90% in SOC associated with macro-aggregates, respectively. This demonstrates that the greatest impact on SOC associated with macro-aggregates was achieved under the SB management practice.

Table 4. Soil aggregate-associated organic carbon under different WSM practices

WSM Practices	Land Slope and Aggregate- Associated SOC Distribution (%)					
	US		MS		LS	
	SOC-MaA	SOC-MiA	SOC-MaA	SOC-MiA	SOC-MaA	SOC-MiA
CS	1.61^d	1.12^a	1.21^d	1.14^a	1.84^d	1.12^a
SB	2.93^a	1.14^a	2.43^a	1.15^a	2.89^a	1.17^a
FJ	2.16^c	1.11^a	2.08^c	1.11^a		
MB	2.77^b	1.13^a	2.17^b	1.12^a		
CV	0.462	0.634	0.467	0.346	0.612	0.642
LSD	0.015	0.018	0.023	0.021	0.043	0.026
R^2	0.956	0.936	0.986	0.968	0.945	0.986
F-t	**	**	**	**	**	**

Means followed by the same letter down each column are not significantly different

US = Upper slope, MS = Middle slope, LS = Lower slope, CS = Control sample, SB = Soil bend, FJ = Fanya-juu, MB = Micro basin, WSM = Watershed management, SOC-MaA = Soil organic carbon associated with macro-aggregates, SOC-MiA = Soil organic carbon associated with micro-aggregates, CV = Coefficient of variance; LSD = Least significance difference; ** = Significant at $p \leq 0.01$.

In areas with varying soil management techniques, the input, deposition, and turnover of litter fall, stumps, and roots from mature trees contribute to the maintenance of SOC associated with both macro-aggregates and micro-aggregates. According to several researches, higher SOC content is anticipated to further improve soil aggregate stability and play a critical role in the rehabilitation of degraded lands (Monroe *et al*., 2016; Wu *et al*., 2021).

3.4 Nutrients availability under soil management practices and its correlation with soil glomalin contents

As shown in Figure 1, nutrient availability increased positively in correlation with soil glomalin content. It was observed that nutrient availability positively and significantly ($p < 0.05$) correlated with both total glomalin and easily-extractable soil glomalin. Similar correlations were reported by Liu *et al.* (2020) and Wu *et al.* (2021), indicating a positive relationship between soil glomalin content and nutrient availability. Compared to control samples, the availability of nutrients increased in correlation with soil glomalin content under the three soil management practices, in the order of FJ < MB < SB < CS across all land slopes.

When comparing the effects of land slopes, nutrient availability increased in the order of MS < US < LS under different soil management practices that influenced soil glomalin content. The maximum increments of macronutrients compared to the control treatment were observed under the SB management practice, with increases of 66.98%, 73.63%, >100%, 58.26%, and >100% for Ca^{2+}, Mg^{2+}, K^{+}, P, and N, respectively, in various land slopes. This improvement may be attributed to long-term soil management practices that enhanced soil glomalin content and other physicochemical properties, thereby increasing nutrient availability.

These findings are consistent with reports by Liu *et al.* (2020) and Xie *et al.* (2015) regarding changes in macronutrient content under different land management practices and soil glomalin levels. However, the effects of soil management practices and the correlation of soil glomalin content with micronutrients were less consistent. For example, Fe^{2+} showed a 3.41% increase under FJ management but decreased under the other practices. Zn^{2+} exhibited the highest increase (>100%) under SB management in the lower and middle slopes, but only a 0.81% increase in the upper slope. Mn^{2+} increased by 8.34%, 7.78%, and 21.66% in the upper, middle, and lower slopes, respectively, under the SB management practice.

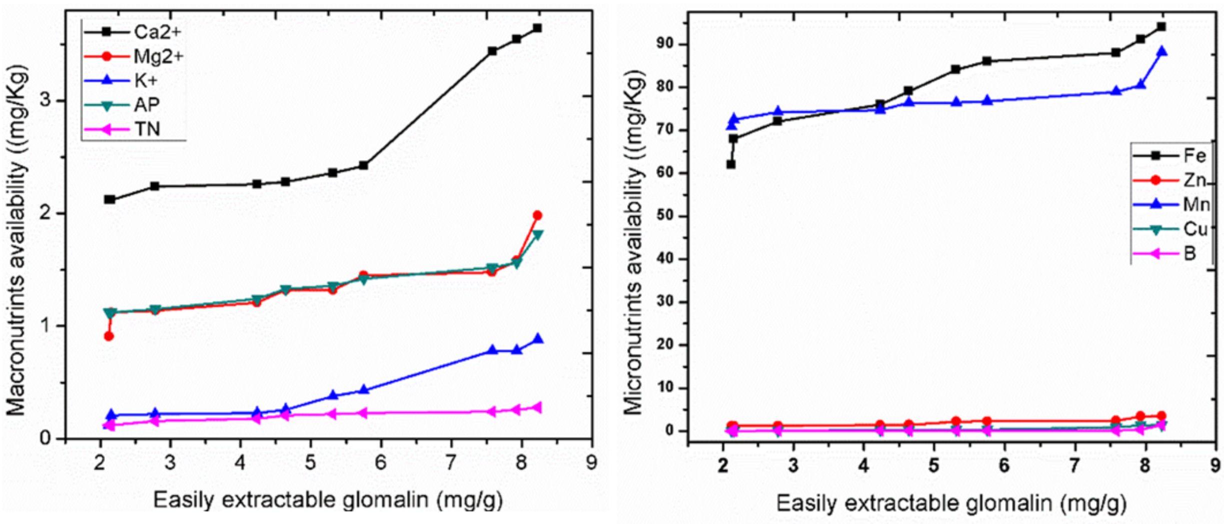

Figure 2. Correlations between soil glomalin contents and macronutrients (left) and micronutrients (right) availability

On the other hand, Cu^{2+} exhibited increases of over 100% in both the upper and lower slopes but showed no increment in the middle slope under the SB management practice. This variation may be attributed to the fact that the availability of micronutrients is fundamentally governed by complex soil chemical reactions. These reactions are primarily regulated by key soil properties, including pH, organic matter content, and redox potential. Consequently, managing these properties through specific soil conservation practices directly influences the bioavailability of micronutrients (Fageria *et al*., 2002).

4 Conclusions

This study identified the most effective watershed management (WSM) practice among those implemented in the Amalake watershed, Southern Ethiopia. The findings revealed that for watersheds characterized by rugged topography and degraded ecology, the soil bund (SB) management practice is the most effective soil management approach. Soil aggregate stability, physicochemical properties, and nutrient availability were significantly influenced by the WSM practices, particularly by the SB method. Therefore, to effectively protect soil resources, restore degraded lands, and enhance soil quality and nutrient availability, soil bunds are recommended as the best management practice for this type of ecology and landscape. Finally, we recommend investigating the impacts of WSM on other soil physicochemical properties to achieve a holistic understanding of the long-term effects of soil management practices.

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